PAPERS AND PROCEEDINGS OF

THE ROYAL SOCIETY OF TASMANIA

Edited by M. Davies

and Published by the Society

Hobart

Tasmania

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30 NOVEMBER 2006

VOLUME 140

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Printing Authority of Tasmania

ISSN 0080-4703

NOVEMBER 2006

VOLUME 140

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PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA
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TASMANIA

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Publication of this volume was generously supported by the Government of Tasmania and the University of Tasmania.

PALAEODISTRIBUTION OF PYGMY-POSSUMS IN TASMANIA

by Jamie M. Harris and Jillian M. Garvey

(with one text-figure and one table)

Harris, J.M. and Garvey, J.M. 2006 (30.xi): Palaeodistribution of pygmy-possums in Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 140: 1–10. ISSN 0080-4703. School of Environmental Science and Management, Southern Cross University, New South Wales 2480, Australia (JMH*); Archaeology Program, School of Historical and European Studies, LaTrobe University, Victoria 3086, Australia (JG). *Author for correspondence.

This work is a contribution towards documenting the fossil distribution of the pygmy possums *Cercartetus lepidus* and *C. nanus* (Marsupialia: Burramyidae) in Tasmania. We provide locality data and bibliographic sources for 15 Quaternary fossil sites important for these species (i.e., Beeton Rockshelter on Badger Island, Cave Bay Cave on Hunter Island, Bone Cave, Derwent River Shelter 7, Kutikina Cave, Mackintosh Cave, Main Drain, March Fly Pot, Newdegate Cave, Nunamira, Ouse River Shelter 7, Peramerpar Meethaner, Pseudocheirus Cave, Warhol, and Warreen Caves on mainland Tasmania). Dates available for these sites span the period 3960 ± 60 to 34,790 ± 510 years ago. We also draw attention to a Late Oligocene fossil locality at Geilston Bay which produced an undescribed *Cercartetus*-like species. The recorded palaeodistribution of pygmy-possums in Tasmania is widespread, with sites on two offshore islands, and also in the southern, south western, and western areas of mainland Tasmania.

Key Words: *Cercartetus, nanus, lepidus*, Tasmania, distribution, fossil, Burramyidae.

INTRODUCTION

The eastern pygmy-possum *Cercartetus nanus* and little pygmy-possum *C. lepidus* are diminutive burramyid marsupials that occur in Tasmania (15–43 g and 6–9 g respectively; Strahan 1995). Modern Tasmanian records for *C. lepidus* and *C. nanus* indicate that both species are widely distributed (Rounsevell *et al.* 1991, Munks *et al.* 2004). However, the recorded modern Tasmanian range of *C. lepidus* is more extensive than that of *C. nanus* (see range maps in Munks *et al.* 2004). Differences in the distribution of these two species reflect both their biogeographical history and subtle differences in their ecological requirements. Most records for *C. nanus* in Tasmania are from wet forests/rainforests (Green 1973, Watts 1987), whilst those for *C. lepidus* are from more xeric communities including dry sclerophyll forests and heathlands (Green 1979, Wall 1985). However, in some areas of Tasmania the range and habitats of these species are reported to overlap.

Outside Tasmania, *C. lepidus* is found on Kangaroo Island, South Australia (SA) (Aitken 1967, 1974), southeast mainland SA (Aitken 1977) and northwest Victoria (Ward 1992, Menkhorst 1995). *Cercartetus nanus* is found as far north as southeast Queensland (Harris *et al.* in press), through parts of mainly coastal New South Wales (NSW) (Bowen & Goldingay 2000) and Victoria (Harris & Goldingay 2005a), and west to the southeast of SA (Carthew 2004, van Weenen & Harris 2006). On the mainland, the status of *C. lepidus* and *C. nanus* varies throughout their respective ranges from "Common" to "Vulnerable" (see Tulloch 2004). In Tasmania, the current status of both burramyids is recognised as "not threatened", but this is based on incomplete information and is in need of review (Duncan & Taylor 2001, Munks *et al.* 2004).

A long-term perspective on the status and distribution of pygmy-possums can be gained by reference to information derived from their fossil occurrence in cave deposits. They are incorporated into the fossil record because several carnivorous marsupials and owl species prey on pygmy-possums (and other small mammals) and deposit bones in caves as scats or regurgitated pellets; and also because pygmy-possums are susceptible to some pitfall-style caves (see Harris & Goldingay 2005b). Caves provide excellent preservation sites for small mammal remains, and excavation and analysis at numerous cave sites in southern Australia have provided valuable information on past distribution patterns of mammalian species (e.g., Wakefield 1972, Archer 1974, Baynes 1987, Archer *et al.* 1991, Baird 1991, Baynes & Johnson 1996).

In the case of the mountain pygmy-possum *Burramys parvus*, an assessment of its fossil distribution has shown a dramatic reduction in geographic range during the Late Pleistocene (Broome & Mansergh 1989, Brammall 1993, Mansergh & Broome 1994). A reduced distribution for *C. lepidus* is also apparent as fossil bones referable to this species have been discovered in areas where it is now extinct, i.e., in eastern NSW (Ride 1960) and eastern Victoria (Wakefield 1960). A preliminary investigation of the fossil occurrence of *C. nanus* in Victoria (Harris & Goldingay 2005b) suggested that this species has not undergone a broad contraction of geographic range like *B. parvus* or *C. lepidus*. Examination of the distribution of fossil sites in South Australia however, indicates a recent range contraction (Harris in press). At present, there is very little published information on pygmy-possum fossil remains from Tasmania, which limits current understanding of biogeographic patterns in the distribution of pygmy-possums through time across Australia. Hence, the aims of this contribution are: (i) to document available information on the fossil localities for pygmy-possums in Tasmania; (ii) plot the distribution of pygmy-possum fossil sites; and (iii) identify modes of accumulation involved at the various sites.

METHODS

The Southern Forests Archaeological Project (SFAP) CD (McWilliams *et al.* 1999), and several unpublished theses were examined with reference to pygmy-possum material

recovered from Tasmanian archaeological cave sites. Records of Tasmanian fossil burramyids were also searched for in several journals including *Australian Archaeology, Papers and Proceedings of the Royal Society of Tasmania, Tasmanian Cave and Karst Research Group Journal*, and *The Tasmanian Naturalist* (Harris 2005). Several other published sources were also reviewed (see papers cited in Harris & Goldingay 2005b). Additionally, enquiries were made with the palaeontology divisions of the Australian Museum (AM), Sydney; Museum Victoria (MV), Melbourne; Queen Victoria Museum and Art Gallery (QVMAG), Launceston; and Tasmanian Museum and Art Gallery (TMAG), Hobart. Geographic information for identified fossil sites was obtained from the relevant literature, the Geoscience Australia online place-name search (http://www.ga.gov.au/map/names/), or directly from topographic maps. We also sought information from the Tasmanian Aboriginal Site Index (TASI), administered by the Department of Tourism, Parks, Heritage and the Arts (DTPHA) for the Tasmanian Aboriginal Land and Sea Council (TALSC), the Aboriginal Heritage Office, DTPHA, academic staff in the School of Zoology, University of Tasmania, and from members of the Southern Tasmanian Caverneers Inc.

A multitude of taphonomic (preservation) biases can affect the abundance of pygmy-possums (and other small mammals) in cave sites. These include dietary selectivity, habitat preferences and physiological requirements of predatory accumulators, disparity in the ways that prey is eaten and digested, differential disappearance rates of prey remains, and temporal variability of predator and prey populations (see Garvey 1999, Harris & Goldingay 2005b). Other factors include dispersal, scattering, or disintegration of bone due to gravity, stream wash, or the action of scavengers, including cave-trapped animals. Due to these and other biases operating inconsistently at the sites, we have not attempted to interpret stratigraphic data on the abundance of pygmy-possums, and have limited our investigation to reviewing whether *Cercartetus* material was reported as present/absent from the sites. This paper provides the first published list of known localities for fossil burramyids in Tasmania.

RESULTS

Material referable to *Cercartetus* has been reported from 15 Late Pleistocene and/or Holocene fossil sites in Tasmania (table 1). These include Cave Bay Cave on Hunter Island (Bowdler 1974a, 1982, 1984) and Beeton Rockshelter on Badger Island (Sim 1998), both to the north of mainland Tasmania (fig. 1). Pygmy-possum fossil and sub-fossil sites are also known from caves in the southern, southwestern and western areas of mainland Tasmania. The southern sites include Pseudocheirus Cave and March Fly Pot, which are two vertical caves in the Ida Bay karst, south of Lune River (Clarke 1988a, Muirhead 1990); Nunamira (formerly Bluff Cave) and Warhol (a vertical cave), both in the Florentine Valley section of the Junee-Florentine karst (Eberhard 1988, Cosgrove *et al.* 1990, Cosgrove 1991, 1996a, Cockbill 1999, McWilliams *et al.* 1999); and Newdegate Cave (H-1; formerly HX-7) in the Hastings karst, north of the Lune River (Clarke 1999, 2000). Southwestern sites are Bone Cave in the Weld River Valley (Northwood 1990, Allen 1996, McWilliams *et al.* 1999); Warreen (formerly known as M86/2) in the Maxwell River Valley (Allen *et al.* 1989, Cockbill 1999, McWilliams *et al.* 1999), and Kutikina Cave (formerly Fraser Cave) on the Franklin River (Smith & Sharp 1993, Geering 1983, Jones *et al.* 1983, Kiernan *et al.* 1983; Jones 1990; Garvey 2006) (fig. 1). Sites in western Tasmania are Main Drain, a limestone cave at Bubs Hill, east of Queenstown (Clarke 1988b, 1989) and Mackintosh Cave on a tributary of the Pieman River (Stern & Marshall 1993, McWilliams *et al.* 1999). Sites outside these areas are the Ouse River Shelter 7 rockshelter (ORS 7) in the Shannon River Valley (Cosgrove *et al.* 1990, Cosgrove 1991, 1996b, McWilliams *et al.* 1999), Permerpar Meethaner rockshelter in the upper Forth Valley (Cosgrove 1995, 1999), and Derwent River Shelter 7 rockshelter (DRS 7) on the Derwent River (Garvey 1999).

Of particular significance for the antiquity of pygmy-possums is a Late Oligocene fossil locality at Geilston Bay (Tedford *et al.* 1975, Rich *et al.* 1982, Tedford & Kemp 1998). A single right lower incisor collected from this site was the only identified remains of a species assignable to the family Burramyidae. The incisor was described by Tedford & Kemp (1998:16) as "most similar to those of *Cercartetus* and *Burramys*, especially the former, although it is about twice the size of any living species of that genus". Further work may provide evidence to determine whether it is indeed a burramyid.

The literature pertaining to some of these sites provides information on counts of Minimum Number of Individuals (MNI) from different stratigraphic units. For example, for Cave Bay Cave, Bowdler (1984) reported a total of 52 *C. nanus*, with these being from the "Upper Midden" (MNI=25), "Sterile Layer" (MNI=10), "Lower Midden" (MNI=2), "Upper Pleistocene < 19,000 BP" (MNI=2) and "Lower Pleistocene ≥ 19,000 BP" (MNI=13). For *C. lepidus*, Bowdler (1984) reported that three specimens were collected, one from the "Lower Midden" and two from the "Lower Pleistocene ≥ 19,000 BP" unit. Clarke (1988b, 1989) recorded a single fragmented burramyid specimen from Main Drain, tentatively assigned to *C. nanus*. In the case of the two vertical caves at Ida Bay, there were two *C. nanus* and one *C. lepidus* retrieved from March Fly Pot, and for Pseudocheirus Cave there were 19 *C. nanus* and three *C. lepidus* retrieved (Muirhead 1990). For Warhol, Eberhard (1988) reported a single *Cercartetus* specimen that was cautiously assigned to *C. lepidus*.

In his study of the owl pellet remains from Newdegate Cave, Clarke (2000) recorded two specimens of both *C. nanus* (mandible and humerus) and *C. lepidus* (mandibles). For DRS 7, Garvey (1999) identified remains of *C. nanus* (MNI=26) and also some some fragmentary remains attributed to *Cercartetus* sp. (MNI=8), which may have been either *C. nanus* or *C. lepidus*. For Permerpar Meethaner, counts of *C. nanus* specimens in the excavated material have not been published, but Cosgrove (1995:94) stated that this species was "identified in all spits". For Nunamira and ORS 7, Cosgrove (1991) presented preliminary stratigraphic data for *Cercartetus* spp., although these data have now been updated by the SFAP database (McWilliams *et al.* 1999). Similarly, preliminary counts of *C. lepidus* and *C. nanus* in several unpublished theses (i.e., Warreen–Cockbill 1999; Bone Cave–Northwood 1990) are also superseded by McWilliams *et al.* (1999).

The SFAP database currently contains records of *Cercartetus* material excavated from five caves in Tasmania (Bone Cave, Mackintosh, Nunamira, ORS 7 and Warreen). For Bone Cave, two *C. nanus* left mandibles were recorded from Square B spit 2 (ID=29753) and Square B spit 3 (ID=29841). For Mackintosh, the database indicates that 11

TABLE 1
Location and reported ages of fossil *Cercartetus* remains in Tasmania.

Site Name	Cl	Cn	Cspp.	KI code	Site code	TASI code	Origin	Age (yr BP)	Latitude	Longitude	Sources
Cave Bay Cave	+	+	-	H1-X1	-	0031	MS, OP	22,750±420 to 18,550±600	40° 34' S	144° 45' E	Bowdler 1974a, 1982, 1984
Beeton Rockshelter	+	+	-	-	-	5558	MS, OP	23,180±1280	40° 18' S	147° 52' E	Sim 1998, Cosgrove 1999
DRS 7	-	+	+	-	DRS7	4057	OP	3960 ± 60	42° 20' S	146° 44' E	Garvey 1999
Permerpar Meethaner	-	+	-	-	-	4434	MS, OP	33,850±450 to 33,280±420	41° 42' S	146° 05' E	Cosgrove 1995, 1999
Mackintosh Cave	-	+	-	-	LM90/1	4551	MS	17,030±430 to 14,820±140	41° 43' S	145° 40' E	McNiven *et al.* 1993, Stern & Marshall 1993, McWilliams *et al.* 1999
Nunamira Cave	+	+	+	JF-53	-	4046	OP	30, 750±1340 to 11,600	42° 37' S	146° 26' E	Cosgrove 1991, 1996a, McNiven *et al.* 1993, Cockbill 1999, McWilliams *et al.* 1999; Garvey unpubl. data
ORS 7	-	-	+	-	ORS 7	2089	OP	30,840±480 to 2,450±70	42° 05' S	146° 50' E	Cosgrove *et al.* 1990, Cosgrove 1991, 1996b, McWilliams *et al.* 1999
Bone Cave	+	+	-	-	-	1790	MS	29,000±520 to 13,700±860	42° 50' S	146° 27' E	Goede & Bada 1985, Northwood 1990, McNiven *et al.* 1993, Allen 1996, McWilliams *et al.* 1999
Pseudocheirus Cave	+	+	-	IB-97	-	-	OP, PF	12,800 to 400	43° 10' S	146° 40' E	Clarke 1988a, Muirhead 1990
March Fly Pot	+	+	-	IB-46	-	-	PF	12,800 to 400	43° 10' S	146° 40' E	Muirhead 1990
Warhol	-	+	-	JF-392	-	-	PF	Holocene – Recent	42° 42' S	146° 30'E	Eberhard 1988
Warreen	+	+	-	-	M-86/2	3786	OP	34,790±510 to 15,960±310	42° 37' S	145° 55' E	Allen *et al.* 1989, McNiven *et al.* 1993, Cockbill 1999, McWilliams *et al.* 1999
Main Drain	-	+	-	BH-8	-	-	PF	Holocene – Recent	42° 07'S	145 °46'E	Clarke 1988b, 1989
Newdegate Cave	+	+	-	H-1	-	-	OP	Holocene – Recent	43° 22' S	146° 50' E	Clarke 1999, 2000
Kutikina Cave	+	-	-	F-34	-	485	OP	19,770±850 to 14,840±930	42° 31' S	145° 46' E	Garvey 2006
Geilston Bay (*Cercartetus*-like sp)	-	-	?	-	-	-	-	23 Ma	42° 50' S	147° 21' E	Tedford & Kemp 1998

Cl= *C. lepidus*, Cn= *C. nanus*, Csp. = *Cercartetus* sp. KI code = Karst Index alphanumeric code assigned to the respective caves by the Australian Speleological Federation. Site Code = Identification codes assigned by individual research groups. TASI code = Tasmanian Aboriginal Site Index. Origin: OP = Owl Pellet, MS = Mammal Scat, PF= Pitfall. A dash (-) indicates that the data are unknown or not available. The age of the material is years before present (yr BP) provided by the source indicated. Ma = Millions of years ago.

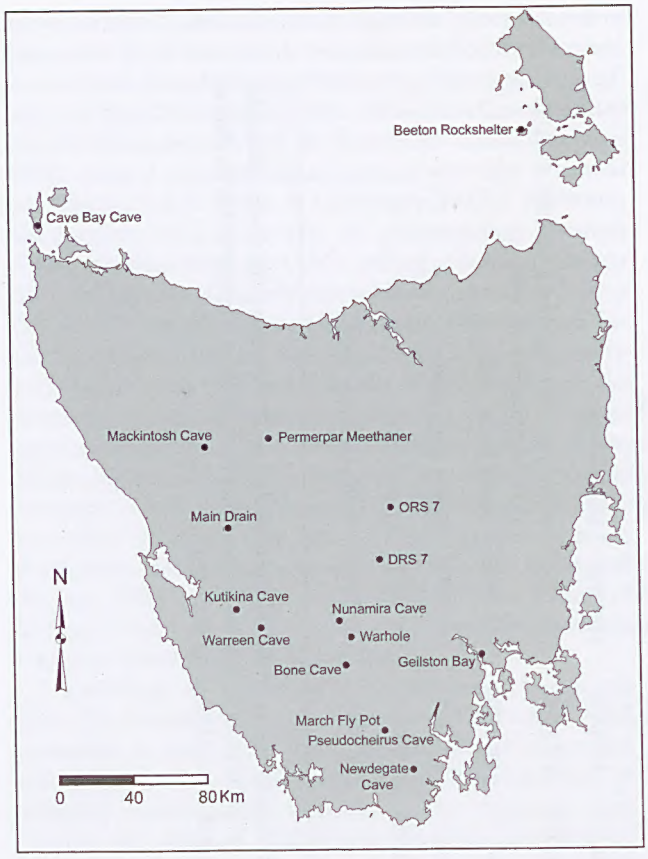

FIG. 1 — Late Pleistocene and/or Holocene fossil sites for Cercartetus *in Tasmania.*

bone fragments of *Cercartetus* spp. ("pygmy-possum; species unknown") were recorded. Cosgrove (1991) explained that no attempt was made to separate *C. lepidus* and *C. nanus* because of their similarity. Mackintosh *Cercartetus* material included mandibles, maxilla and long bones (humerus, radius, ulna, tibia), and were collected from square/spits designated as HN7 (IDs=1015, 1046, 1071; 1072; 1073), GO4 (ID=7455), HM13 (ID=10871) and GL5 (IDs=1940; 1941; 1942; 1968). For Numamira, the database contained 14 entries for "*Cercartetus* spp." representing 28 mandibles or maxillae (all from Square A1, Cell Z, spits 1–7, and Square B1, Cell W, spits 5–7). The Nunamira material is held by TALSC and recent examination of some of this collection allowed verification of the presence of both *C. nanus* and *C. lepidus* (J. Garvey unpubl. data). For ORS 7, only two mandibles of "*Cercartetus* spp." were recorded on the database, from Square B1, spit 6. For Warreen, there were 62 elemental specimens of *C. lepidus*, and 71 of *C. nanus*. The Warreen pygmy-possum bones excavated are mainly left and right mandibles, but also include various other skeletal elements. At Warreen, *C. lepidus* was collected from Square A (spits 11 and 16) and Square B (spits 32, 35, 42–45, 47–58, 60 and 61). The Warreen *C. nanus* was collected from Square A (spits 8, 10, 11–17, 19) and Square B (spits 32, 42, 46, 50, 52, 53, 55, 56, and 59) (see McWilliams *et al.* 1999).

Large mammal bones, particularly those of *Macropus* and *Vombatus*, were found in large numbers during archaeological studies of several of the caves referred to, and are thought to have been accumulated by humans (see Jones 1990, Cosgrove *et al.* 1990, Stern & Marshall 1993, Cosgrove 2002; Garvey 2006). However, owls and marsupial carnivores are the principal accumulators of the majority of small mammal species, nothwithstanding that pitfalls have also accumulated significant numbers.

For Cave Bay Cave, Bowdler (1974b:698, 1984:88) attributed the accumulation of *Cercartetus* material (and also *Antechinus* and murids) to owls, "with the masked owl (*Tyto novaehollandiae*) considered the most likely candidate". Remains of larger mammals in this deposit were attributed to accumulation by Tasmanian devils (*Sarcophilus harrisii*), quolls (*Dasyurus* spp.) or humans. For Nunamira, Cosgrove (1991:260) stated that "the most likely source of [the small mammal] bone was regurgitated owl pellets", noting several hollows in the roof of Nunamira, which "would serve well as owl roosts". Cosgrove (1991) did not speculate on the identity of the owl species involved, but in subsequent publications it has been suggested that owls of the genus *Tyto* were responsible (e.g., McNiven *et al.* 1993).

For ORS 7, Cosgrove (1991:299) favoured owl predation as the most likely explanation for accumulation of *Cercartetus* and other small mammal remains because the bone was in "relatively good condition". For Warreen, owl-pellet bone is most common in the lower levels of the deposit (McNiven *et al.* 1993). For Bone Cave, fossil material recovered was highly fragmented and generally consistent with damage caused by marsupial carnivores (Northwood 1990, McNiven *et al.* 1993, Stern & Marshall 1993). Northwood (1990) believed that the eastern quoll *Dasyurus viverrinus* was responsible for the accumulation of small mammal remains in Bone Cave, which was supported by the discovery of *D. viverrinus* bones in the assemblage. Based on the size range of the bone fragments McNiven *et al.* (1993) agreed that *D. viverinnus* was primarily responsible, although it was noted that *Sarcophilus harrisii* may also have contributed some scat remains at this site. For Mackintosh Cave, Stern & Marshall (1993) implicated *D. maculatus*, stating that faunal composition and their relative abundances compared favourably with its diet. Further support for this conclusion came from the pattern of surface damage observed on the bones of the prey species, which was more characteristic of *D. maculatus* than it was of *S. harrisii* (also see Marshall & Cosgrove 1990). However, bones from larger prey species present in the assemblage may have been the result of the activity of *S. harrisii* (McNiven *et al.* 1993, Stern & Marshall 1993).

For Beeton Rockshelter, Sim (1998) suggested that most terrestrial bones recovered fit the criteria for *S. harrisii* scat remains (following Marshall & Cosgrove 1990). However, Sim (1998:150) noted that the "murid and possibly other small mammal bones most probably originate from owls roosting and raptors perching in the shelter, although quolls may also be responsible for a component". At Permerpar Meethaner, most bone can be attributed to marsupial carnivore activity and this is supported by the discovery of old coprolitic material and of tooth marks on some bones. However, remains of smaller mammals in the lower portion were thought to be derived from owl pellet deposition (Cosgrove 1995). Warhol is a pitfall trap, and the small mammal remains present (including *C. lepidus*) are thought to have accumulated via an "abrupt shaft with vertical and overhanging walls" (Eberhard 1988:53). March Fly Pot was probably also a pitfall for *Cercartetus* (Muirhead 1990). The *Cercartetus* in Pseudocheirus Cave are thought to have been first accumulated by owls and then "washed from an owl deposit at a higher region of the cave before being deposited" (Muirhead 1990:18). However, this cave has nearly vertical walls, and because suitable owl roosting

alcoves are absent, it is more likely these remains accumulated from pitfalls (A. Clarke *pers. comm.* 2006). At DRS 7, Garvey (1999) found that owls accumulated the small mammals, but post-depositional effects prevented the identification of the species of owl.

The fossils from Badger Island (Beeton Rockshelter) and Hunter Island (Cave Bay Cave) are Late Pleistocene in age, dating to 24–21 ka (ka= thousand years ago) and 22–18 ka respectively (table 1). Most mainland Tasmanian sites for fossil pygmy-possums are also Late Pleistocene and span 35–12 ka, including bones collected from Warreen (35–15 ka), Peramerpar Meethaner (34–32 ka), Nunamira (32–12 ka), Bone Cave (30–13 ka), Kutikina Cave (20–14 ka) and Mackintosh Cave (16–15 ka). The ORS 7 site (31–2 ka) incorporated both Late Pleistocene and Holocene material. This is probably also true for March Fly Pot and Pseudocheirus Cave, which were inferred to be around 13–0.4 ka. There are also three undated deposits (Warhol, Main Drain, and Newdegate Cave) that are thought to be of Holocene to recent age. The other sites are the Holocene assemblage at DRS 7 (4 ka) and the Geilston Bay Oligocene material (~23 Ma).

DISCUSSION

With impacts of climate change on biota thought to be rapidly increasing (Hughes 2003), detailed understanding of prehistoric ranges is important, particularly for those species like *Burramys* that are suggested to be at risk of climate-induced extinction (Mansergh & Broome 1994). Of Tasmanian material that can be confidently assigned to *Cercartetus*, the dated ages range from 3960 ± 60 years (y) (DRS 7) to 34,790 ± 510 y (Warreen) (table 1). However, the reliability of the radiocarbon C^{14} dating (table 1) requires comment. The Cave Bay Cave date (22,750 ± 420 y) is one of a sequence of four dates between 14 and 23 ka that apparently agree well with stratigraphic and chronological evidence (Murray *et al.* 1980, Goede & Bada 1985). The series of dates for other sites are mostly, but not invariably, in stratigraphic order (see Cosgrove 1989, 1995, Stern & Marhall 1993, Jones 1995, Allen 1996). The concurrence of around 120 C^{14} dates across seven sites (McWilliams *et al.* 1999) suggests that the chronology is an accurate and robust reflection of events. Nevertheless, because C^{14} dating of samples can be subject to various errors (Goede & Bada 1985, Baynes 1999), all the dates reported here should be treated with caution. Corroboration with other dating methods, such as electron spin resonance (ESR), amino acid racemisation (AAR), thermo-luminscence (TL) and uranium-series (see Goede & Bada 1985, Prescott & Robertson 1997, Ayliffe & Veeh 1998, Grün *et al.* 2001) would impart greater confidence in these C^{14} dates.

Identification of the predatory accumulators

Several criteria have been established to differentiate an owl deposit from a mammalian carnivore deposit. In owl deposits the remains of small animals dominate; the largest animals are represented by juveniles; whole skulls and other skeletal elements are represented; and there is only modest fragmentation of the bone (see also Dodson & Wexlar 1979, Marshall 1986, Andrews 1990, Geering 1990, Kusmer 1990, Garvey 1999). In contrast, high fragmentation rates are characteristic of *S. harrisii* and *Dasyurus* sp. coprolites (Marshall & Cosgrove 1990, Northwood 1990, Garvey 1999). Using these criteria, owls have been implicated as the main accumulator of small mammals at six sites – i.e., DRS 7, Kutikina Cave, Newdegate Cave, Nunamira, ORS 7 and Warreen (table 1). In contrast, at Mackintosh Cave and Bone Cave, mammalian predators were identified as the principal accumulators. At Cave Bay Cave, Beeton Rockshelter and Permerpar Meethaner, there is evidence for both avian and mammalian accumulators. However, identification of the specific predatory species involved at each of these cave sites remains ambiguous.

The Tasmanian Masked Owl *Tyto castanops*, Barn Owl *T. alba* and Southern Boobook *Ninox novaeseelandiae* can be nominated as possible avian accumulators, as these are the only owls known to have lived in Tasmania during the Late Holocene (Garvey 1999), and probably during the Late Pleistocene. Possible dasyurid accumulators were the Spotted-tailed Quoll *D. maculatus*, Eastern Quoll *D. viverrinus*, Tasmanian Devil *S. harrisii* and/or Tasmanian Tiger *Thylacinus cynocephalus*. Except for *T. cynocephalus*, there are numerous records for *Cercartetus* falling prey to these predators (see Guiler 1970, Wallis *et al.* 1977, Green *et al.* 1986, Mooney 1992, 1993, Mumbray 1992, McNabb *et al.* 2005). *Thylacinus cynocephalus* was a large predator, now believed extinct, which fed mainly on large animals such as kangaroos and wallabies (Menkhorst & Knight 2001). Hence, it seems reasonable to eliminate *T. cynocephalus* as the accumulator of the small mammal material in Tasmanian cave deposits on the basis that they were unlikely to take such small prey. Although it is possible that *N. novaeseelandiae* contributed a small amount of vertebrate bone to one or more assemblages, it is unlikely that this species was a significant contributor because of its generally insectivorous diet. Precise identification of the predatory species involved at each of the cave sites referred to may be possible at a future date, by using microscopy to search for diagnostic taphonomic signatures such as digestive corrosion patterns or tooth markings, or by quantative re-assessment of skeletal element representation and breakage (see also Northwood 1990, Garvey 1999, McWilliams *et al.* 1999, Harris & Goldingay 2005b). We also emphasise that further research is needed on the taphonomy of pitfall-originated *Cercartetus* remains, focusing particularly on identifying criteria which allow their differentiation from predator deposits.

Past and present distribution of pygmy-possums in Tasmania

The antiquity of the burramyid fossil record in Tasmania (Tedford & Kemp 1998) raises the intriguing possibility that pygmy-possums may have evolved in Tasmania and dispersed to mainland Australia. Conversely, members of this genus may have arrived in Tasmania via the mainland. If the latter hypothesis is correct, *Cercartetus* probably followed the same route as the Aboriginal Tasmanians – across exposed portions of a Bassian land bridge connecting Wilson's Promontory, Flinders Island and northeast Tasmania (Cosgrove 1999). It is calculated that this bridge existed at 55–50 ka, and again at 37–31 ka and most recently at 29–12 ka (Blom 1988, Jones 1995, Cosgrove 1999). However, it is not known how long *Cercartetus* has resided in Tasmania and whether populations migrated during any or all of these alternating periods of land connection and isolation. Present evidence suggests that *C. nanus* and *C. lepidus* were both present in southwest

Tasmania as long ago as 35 ka (Warreen). However, the oldest *Cercartetus* fossils from the mainland are dated to 279 ka (Cathedral Cave, at Naracoorte, in southeast SA; Reed & Bourne 2000, Harris in press). This raises questions concerning the palaeobiogeography and migration of this genus, but further data including re-assessment of radiocarbon dates are needed (see above).

Of particular relevance to future research is the effect of major climatic and vegetational changes on faunal associations in Tasmania during the Late Pleistocene (e.g., MacPhail 1975, Bowler *et al.* 1976, Colhoun 1978, Hope 1978, Jones 1984, 1990, 1995, Augustinas & Colhoun 1986, Cosgrove *et al.* 1990, Colhoun *et al.* 1991, Jordan *et al.* 1991, Kirkpatrick & Fowler 1998, Cosgrove 1999, Reid *et al.* 1999). Currently, based on palynological evidence, it appears that before 45 ka, the Tasmanian vegetation consisted mainly of alpine and subalpine taxa and the forested environments were confined to low altitudes. *Cercartetus* spp. do not tolerate terestrial alpine and treeless subalpine habitats in Tasmania today (Kirkpatrick *et al.* 1993), and so may have had a restricted (or non-existent) distribution in Tasmania prior to 45 ka. Between 44 and 25 ka, the climate was still colder and wetter than today, but in this period *Cercartetus* is known from numerous sites from south-west Tasmania. *Cercartetus* appears to be present in the vicinity of several sites at the height of the last glacial (~18 ka), but populations were probably not abundant or widespread until the onset of warmer and wetter conditions at about 12 ka. The two species are widespread in the southwest region in modern times, with the habitat of *C. nanus* today regarded as "rainforest" and for *C. lepidus* as "dry sclerophyll forest and heathland" (Hocking 1979). However, modern populations do overlap (see range maps in Munks *et al.* 2004) and there is also evidence for this in prehistoric times (i.e., in the vicinity of Cave Bay Cave, Beeton Rockshelter, Bone Cave, Pseudocheirus Cave, March Fly Pot, and Nunamira) (table 1).

Cercartetus is recorded on Hunter Island for the period 22–18 ka, and populations may have become established there at the time of the most recent (29–12 ka) or penultimate (37–31 ka) landbridge. The same may be true for *Cercartetus* on Badger Island (24–21 ka). Modern populations of *Cercartetus* are not recorded from the Hunter Island group (Bowdler 1984) or from Badger Island (Sim 1998), but one or both species could still occur there, as intensive mammal surveys have not been conducted. Munks *et al.* (2004) noted the presence of extant burramyid populations on the larger land-bridge fragments of King Island (*C. nanus*) and Flinders Island (*C. lepidus* and *C. nanus*) (see also Hope 1973). Surveys for pygmy-possums are needed on these smaller islands to discern whether populations are now truly extinct.

The distribution of fossil sites for *Cercartetus* in Tasmania is shown in fig. 1. It is not yet possible to confidently delimit separate maps for *C. lepidus* and *C. nanus*, as discrimination of these two species on the basis of dental and other skeletal material requires specialist attention and the specific identity of many of these fossils needs to be re-assessed (see also Green & Rainbird 1983, Garvey 1999). Nevertheless, the map of fossil *Cercartetus* sites in Tasmania does indicate that the genus had a broad distribution in the Late Pleistocene. We caution that fig. 1 is essentially a reflection of the distribution of cave sites where detailed excavations have taken place. Most of the sites are caves situated in the southern, southwestern, and western areas of Tasmania. In this region there are extensive tracts of karstic carbonate rock (mainly Silurian and Ordovician limestone and Cambrian/ Precambrian dolomites) and these older geological formations are apparently rare in the eastern regions of Tasmania, which may explain the relative paucity of *Cercartetus* fossils outside of the southwest. Obviously, the perceptible palaeodistribution of *Cercartetus* in Tasmania (and on mainland Australia) is restricted to suitable areas where conditions allow the preservation of delicate skeletal material (i.e., in caves and protected rockshelters), where stable climatic conditions prevail with near constant humidity. The collection of pygmy-possum material also requires careful excavation and small sieve sizes; otherwise their bones are likely to be lost (Hall 1975). They may be easily overlooked, especially when the focus of a fossil investigation is on larger taxa. Notwithstanding these potential sources of preservation and collection bias, comparison of Quaternary and present distributions suggest that there are apparently no regions where *Cercartetus* was, but is no longer, found on mainland Tasmania.

Our review of published literature indicates that pygmy-possums were not found among the mammal fossils excavated at a number of sites throughout Tasmania, including at Prion Beach Rockshelter in far southern Tasmania (2070±70; Dunnett 1992); Flowery Gully (7080 ± 420; Gill 1968); Tiata Mara Kominya (formerly Beginners Luck Cave) (80,000 to 12,600±200; Goede *et al.* 1978, Murray 1979, Murray *et al.* 1980, Bowdler 1982, Allen 1996, Goede & Bada 1985); Pleisto Scene Cave (130,000 to 10,100±200; Murray & Goede 1977, Goede *et al.* 1978, Goede & Bada 1985); Cardia Cave (18,000; Jones & Allen 1984); Pallawa Trounta (formerly Acheron Cave) (29,800±720 to 13,000; McNiven *et al.* 1993, McWilliams *et al.* 1999); Maneena Langatick Tattana Emita (10,250±420; Pocock 1992, 1993); Mannalargenna Cave (20,560±290 to 7,960±170; Brown 1993); Louisa Bay (Vanderwal 1979); Stone Cave (16,670±70; McWilliams *et al.* 1999); Warragarra Rockshelter (10,910±110 to 410±60; McWilliams *et al.* 1999), or Titans Shelter (27 ka) (Goede & Murray 1979, Cosgrove *et al.* unpubl. data). The reason why burramyid bones were not reported from these caves is unknown. They may have been absent or too small to be detected in the excavations. The majority of these caves were used as roost sites for owls or den sites for dasyurids so it is expected that *Cercartetus* could be present. There are also a number of vertical (pitfall) caves with significant sub-fossil deposits of currently unstudied mammalian remains in the Bubs Hill, Cracroft, Hastings, Ida Bay, Junee-Florentine, Mole Creek, Mount Weld and Precipitous Bluff karst areas in Tasmania (A. Clarke *pers. comm.* 2006).

There are also many other caves known to contain mammal bone, but thus far only very small samples have been collected from the surface layers of these sites, and at present *Cercartetus* is not recorded. Such localities include Nanwoon Cave (7.2 ka); Main Cave, Montagu (13 ka); Boomer Cave (20 ka); Un-named Cave, Florentine Valley (97 ka); Nelson River Cave (19 ka); and Deena Reena Cave (19 ka) (Goede *et al.* 1978; Kiernan 1982; Goede & Bada 1985; Jones 1995; see also Andrews 1971). There are conservatively about 2800 other caves within Tasmania (Clarke 2005; see also Middleton 1979; Kiernan 1988; Jones 1995), but only a small number of these have been subjected to archaeological or palaeontological study.

CONCLUSION

This paper provides a preliminary account of Tasmanian burramyid biogeography and highlights the need for more detailed palaeontological and archaeological study of caves and rockshelters throughout Tasmania. Further research should involve re-examination of the ORS 7 material to ascertain whether the *Cercartetus* specimens represent *C. lepidus*, *C. nanus*, or both species. Calculation of dates for the faunal assemblages from Warhol, Main Drain and Newdegate Cave would also be desirable. The excavation of new localities is important because "new" fossil pygmy-possum material may be discovered, providing further information on the palaeodistibution of these species. Finding new fossil localities for *C. lepidus* and *C. nanus* in northwestern and northeastern Tasmania would be particularly valuable, as would additional specimens of Tedford & Kemp's (1998) undescribed *Cercartetus*-like species; additionally, it is entirely possible that *Burramys* (see Long *et al.* 2002) may yet be found in Tasmanian cave deposits.

ACKNOWLEDGEMENTS

For information and advice we thank Sandra Bowdler (University of Western Australia), Arthur Clarke (University of Tasmania), Rolan Eberhard (Tasmanian Department of Primary Industries, Water and Environment), Ross Goldingay (Southern Cross University), Noel Kemp (Tasmanian Museum and Art Gallery), and Caleb Pedder and Don Ranson (Aboriginal Heritage Office, Tasmanian Department of Tourism, Parks, Heritage and the Arts). We are also grateful to Greg Luker (Southern Cross University) for producing the figure, and to Richard Cosgrove (La Trobe University), John Long (Museum Victoria) and Kristofer Helgen (University of Adelaide) for commenting on an earlier version of the manuscript.

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(accepted 3 July 2006)

VICARIANCE OR DISPERSAL – TRANS-TASMAN FAUNAL RELATIONSHIPS AMONG THYSANOPTERA (INSECTA), WITH A SECOND SPECIES OF *LOMATOTHRIPS* FROM *PODOCARPUS*

by Laurence A. Mound

(with one plate)

Mound, L.A. 2006 (30:xi). Vicariance or dispersal – trans-Tasman faunal relationships among Thysanoptera (Insecta), with a second species of *Lomatothrips* from *Podocarpus*. *Papers and Proceedings of the Royal Society of Tasmania* 140: 11–15. ISSN 0080-4703. C/- CSIRO Entomology, PO Box 1700 Canberra, ACT 2601, Australia. e-mail: Laurence.Mound@csiro.au

Lomatothrips pinopsidis sp.n. (Insecta:Thysanoptera) is described as the second species of the genus. This species is widespread in Australia on *Podocarpus* and *Callitris* male cones, but the only other species in the genus is from New Zealand breeding in vegetative buds of *Podocarpus*. This is possibly an example of trans-Tasman vicariance, although the thrips fauna of New Zealand is shown to be largely dispersed from Tasmania and mainland Australia.

Key Words: biogeography, thrips, vicariance, Australia, New Zealand, Tasmania.

INTRODUCTION

Tasmania and the mountains of southeastern mainland Australia are subject frequently to a strong westerly air-stream. These winds, occurring at times when high summer temperatures and the rising air masses associated with bushfires lift small organisms high into the air, are known to result in the dispersal of a wide variety of organisms across the Tasman Sea to New Zealand (Close *et al.* 1978). The dispersal of several species of butterflies and moths from Australia to New Zealand was documented by Fox (1978), and this dispersal has more recently been shown to include various Microlepidoptera (Hoare 2001). Moreover, many Australian insects that are specialist feeders on *Eucalyptus* species have become established on planted gum trees in New Zealand, including during the past 20 years five of the small species of jumping plant lice (Psyllidae) (Withers 2001). These westerly air-streams vary in direction and intensity with the seasons, but in summer, 83% of all low-level air parcels from the Sydney area were found to pass over central New Zealand within five days (Sturman *et al.* 1997), and dust particles have been shown to be transported by winds from Australia to New Zealand in 1.5 days (Collyer *et al.* 1984).

Given our lack of knowledge of the Tasmanian fauna of many groups of small organisms, including the insects known as thrips, the existence of trans-Tasman dispersal leads to problems in evaluating endemism, and thus distinguishing vicariance from trans-oceanic dispersal. For example, Stannard (1962) described the Thysanoptera genus *Cartomothrips* for two species, one from Victoria and the other from New Zealand, and inherent in this was the assumption of a trans-Tasman speciation event. In contrast, Mound & Walker (1982a) expressed doubt concerning this possibility, and suggested that the putative New Zealand endemic *C. manukae* Stannard might have dispersed from Tasmania. Subsequently, this species was found in Tasmania (Mound 1996), in association with the same host-plant "Manuka", *Leptospermum scoparium*.

The present paper concerns another Thysanoptera species that is currently considered a New Zealand endemic, *Lomatothrips paryphis* Mound & Walker. This species has recently been found breeding near Auckland in the leaf buds of the native Gymnosperm, *Podocarpus totara* (Martin & Mound 2005). In publishing that host record it was pointed out that a second, undescribed, species of *Lomatothrips* had been taken in southeastern Australia in association with *P. lawrencei*. The purposes of this paper are to describe this second species, indicate its distribution and host range in Australia, and to discuss the distribution of the two *Lomatothrips* species in the light of Thysanoptera faunal relationships between New Zealand and southeastern Australia including Tasmania, these seeming to result more from recent dispersal than vicariance. A further purpose is to draw attention to how little is known of the native thrips fauna of Tasmania.

THRIPS TRANS-TASMAN FAUNAL RELATIONSHIPS

Dispersal from Tasmania and mainland Australia to New Zealand was recognised for seven species of Thysanoptera-Terebrantia (Mound & Walker 1982b), but to these should now be added three of the 19 species that were then considered to be New Zealand endemics (table 1). Of the resultant 10 species, *Karphothrips dugdalei* Mound & Walker is widespread in Tasmania and southern Australia on species of the sword grass genus *Gahnia*, and *Anaphothrips varii* Moulton, *A. woodi* Pitkin and *Parabaliothrips montanus* (Girault) are all associated with various grasses in southeastern Australia. Similarly, *A. dubius* (Girault) sometimes produces large populations on the leaves of various native herbaceous Asteraceae in eastern Australia. Establishment in New Zealand of all five of these thrips species has probably been facilitated by the lack of competing thrips on their favoured host plants. Similarly, the gum tree flower thrips, *Thrips australis* (Bagnall), finds a vacant ecological niche in New Zealand in the flowers of *Eucalyptus*, and suitably vacant niches are similarly available to the Australian orchid thrips, *Dichromothrips spiranthidis* (Bagnall), and Kelly's citrus thrips, *Pezothrips kellyanus* (Bagnall). In contrast, the vastly common Australian plague thrips, *Thrips imaginis* Bagnall, is known in New Zealand from very few specimens, despite being one of the most abundant insects in southern Australia. The failure of this thrips to develop substantial populations might be due to competition from the abundant and equally polyphagous

TABLE 1
Native Australian Thysanoptera species in New Zealand

Terebrantia: Thripidae
Anaphothrips dubius (Girault)
Anaphothrips varii Moulton
Anaphothrips woodi Pitkin
Dichromothrips spiranthidis (Bagnall)
(= *Dichromothrips maori* Mound)
Karphothrips dugdalei Mound & Walker
Pezothrips kellyanus (Bagnall)
Parabaliothrips montanus (Girault)
(= *Pseudanaphothrips annettae* Mound & Palmer)
Pseudanaphothrips achaetus (Bagnall)
Thrips australis (Bagnall)
Thrips imaginis Bagnall

Tubulifera: Phlaeothripidae - Phlaeothripinae
Apterygothrips australis Pitkin
Apterygothrips collyerae Mound & Walker
Baenothrips moundi (Stannard)
Cartomothrips manukae (Stannard)
Cartomothrips neboissi Mound & Walker
Haplothrips salicorniae Mound & Walker
Hoplothrips poultoni (Bagnall & Kelly)
Lissothrips gersoni Mound & Walker
Macrophthalmothrips argus (Karny)
Psalidothrips taylori Mound & Walker
Sophiothrips greeensladei Mound & Walker
Strepterothrips tuberculatus (Girault)
Teuchothrips annulosus (Priesner)
Teuchothrips disjunctus (Hood)

Tubulifera: Phlaeothripidae - Idolothripinae
Carientothrips badius (Hood)
Carientothrips loisthus Mound
Emprosthiothrips bogong Mound
Heptathrips cumberi Mound & Walker
Idolothrips spectrum Haliday

New Zealand flower thrips, *Thrips obscuratus* (Crawford). However, such a suggestion of competitive exclusion does not seem to apply to another polyphagous Australian flower thrips, *Pseudanaphothrips achaetus* (Bagnall), because this has been found in New Zealand in considerable numbers.

Considering the Thysanoptera-Tubulifera fauna of New Zealand, Mound & Walker (1986) indicated that 17 species appeared to be immigrants from Australia. This total has subsequently risen to 19 (table 1), and most of these species are also now known from Tasmania. Again, the biology of these species pre-adapts them to be successful trans-Tasman migrants. All five listed Idolothripinae feed on fungal spores, and six of the Phlaeothripinae feed on fungal hyphae (*Baenothrips moundi* Stannard and *Psalidothrips taylori* Mound & Walker in leaf litter; *Hoplothrips poultoni* (Bagnall & Kelly), *Macrophthalmothrips argus* (Karny), *Sophiothrips greensladei* Mound & Walker and *Strepterothrips tuberculatus* (Girault) on dead twigs). The other species exhibit a range of biologies; *Apterygothrips australis* Pitkin lives in grasses; *Apterygothrips collyerae* Mound & Walker is predatory on mites and possibly thrips larvae on shrubs and trees; the two *Cartomothrips* species live on plants, *Kunzea* and *Leptospermum* species, that themselves have a trans-Tasman distribution; *Haplothrips salicorniae* Mound & Walker is common on the widespread salt-marsh plants known as glassworts or samphires; *Lissothrips gersoni* Mound & Walker lives amongst mosses and liverworts; *Teuchothrips annulosus* (Priesner) feeds on the leaves of species of *Ozothamnus* and possibly *Cassinia*; *Teuchothrips disjunctus* (Hood) distorts the leaves of the common garden plant *Callistemon citrinum*. Thus 18 of these species may well have dispersed into New Zealand naturally on the westerly winds, although the last one mentioned has more probably been moved by the horticultural trade. A further species with a trans-Tasman distribution is *Nesothrips propinquus* (Bagnall), but this spore-feeding thrips that lives amongst dead grasses is considered to have originated in New Zealand, from where it has been widely distributed along the sailing ship route to Europe, presumably in hay and straw (Mound 1983).

Given the large number of Thysanoptera species that apparently have dispersed across the Tasman and successfully established in New Zealand, it is not possible to assume that the distribution of the two species of *Lomatothrips* represents vicariance. The New Zealand species *L. paryphis* has not been found in Australia on any of the available gymnosperms. However, no surveys for thrips have been conducted on Tasmanian gymnosperms at suitable times of the year. The two species of *Lomatothrips* appear to have very different larval biologies; *L. paryphis* has been reared from vegetative terminal buds, whereas the new species described below is associated with male cones on various Pinopsida, presumably feeding on pollen. On balance, the distribution of *Lomatothrips* seems likely to be due to vicariance, but this suggestion requires field testing in Tasmania by surveying potential gymnosperm host plants.

Lomatothrips Mound & Walker

Lomatothrips Mound & Walker, 1982b: 67. Type species *L. paryphis*, by monotypy.

Lomatothrips shares an interesting synapomorphy with the members of the Australian genus *Pseudanaphothrips* Bagnall as well as those of the large genus *Frankliniella* Karny that is so dominant throughout the Americas but particularly in the Neotropics (Mound & Marullo 1996). This shared character state is the presence of paired ctenidia anterolateral to the spiracles on the eighth abdominal tergite. Mound (2002) suggested that *Pseudanaphothrips* might be the sister-genus of *Frankliniella*, but in any future analysis of generic relationships *Lomatothrips* will also need to be considered. The species of all three genera also share the following two character states, although these are probably plesiomorphies: three pairs of ocellar setae on the head; both pairs of metanotal setae close to the anterior margin of this sclerite (see below). In contrast to the other two genera, both *Lomatothrips* species have the setal row on the first vein of the forewing widely interrupted not continuous, their antennae have seven not eight segments, and they share the curious autapomorphy of a craspedum on the posterior margin of the second to seventh abdominal tergites. The original and detailed generic diagnosis also applies to the new species described below, except for the character states indicated in the key. Despite this, the original statement that the metanotal median setae are "not at the anterior margin" requires comment. The position of these setae is variable

in the available material of both species, being within the anterior quarter of this sclerite but with one or both setae occasionally close to or at the anterior margin.

Key to *Lomatothrips* species

1. Abdominal tergite VIII posteromarginal comb of microtrichia interrupted medially; pleurotergites with a craspedum; ocellar setae pair III arising on tangent joining anterior margins of posterior ocelli; forewing first vein with 3 setae on distal half; mouth cone extending to fore coxae ..... *paryphis*
-. Abdominal tergite VIII posteromarginal comb of microtrichia complete medially; pleurotergites without a craspedum; ocellar setae pair III arising between posterior ocelli posterior to tangent joining their anterior margins; forewing first vein with 2 setae on distal half; mouth cone extending well beyond fore coxae ..... *pinopsidis*

Lomatothrips paryphis Mound & Walker

Lomatothrips paryphis Mound & Walker, 1982b: 67.

This, the original species in this monobasic genus, was based on 22 female specimens extracted from leaf litter at several sites in both North and South Island, New Zealand. Unfortunately, although 11 of these specimens were micropterae there was no precise host plant association available with any of them. Subsequently, the species was found breeding near Auckland, and larvae were reared in the leaf buds of the New Zealand native Gymnosperm, *Podocarpus totara* (Martin & Mound 2005). No males have been seen, despite considerable numbers of larvae and adults being collected in two successive years.

Lomatothrips pinopsidis sp. n.

Female macroptera. Colour of body and legs mainly yellow; tergites II – VII with median light brown area; abdominal segment X brown at apex, major setae on IX–X light brown; ocellar region sometimes slightly shaded, compound eyes with 4 ommatidia pigmented and slightly enlarged; mouth cone apex often dark; antennal segment I white, II – VII brown; forewing pale. Head broad (pl. 1A); ocellar triangle wider than long, ocellar setae I small and arising near inter-antennal projection, III arising between posterior ocelli; frons with 6 pairs of setae, 2 long pairs at anterior, 3 shorter pairs close to eyes, 1 long pair postero-medially; mouth cone massive, extending across prosternum, maxillary palps with 3 segments. Antennae 7-segmented (pl. 1B), segment I without a pair of dorso-apical setae. Pronotum with weak transverse striae; 4 pairs of posteromarginal setae pesent, also 2 pairs of posteroangular setae of which the external pair is much shorter than the inner pair. Mesonotal median setae near posterior margin (pl. 1C). Metanotum with weak sculpture medially, median setae usually slightly posterior to anterior margin (pl. 1C). Mesothoracic furca with weak spinula, metafurca usually with no spinula. Tarsi all 2-segmented. Forewing clavus with 5 marginal and 1 discal setae; first vein with 7 setae on basal third and 2 setae on distal third; second vein with 11 to 13 setae; posteromarginal cilia strongly undulating. Tergite I with transverse sculpture but no craspedum; tergites II – VII with sculpture medially progressively weaker on succeeding segments, posteromarginal craspedum entire; tergite II with 3 lateral marginal setae; tergite VIII posteromarginal comb complete, ctenidia present anterolateral to spiracles (pl. 1D); tergite X with split reaching only mid-point. Pleurotergites with no craspedum; sternites III – VII with marginal craspedum shorter than diameter of a setal base.

Measurements of holotype female in microns. Body length 1300 (paratypes LAM 4404 largest and smallest 1550, 950). Head, dorsal length 75; length to mouth cone apex 250; width 140; ocellar setae III 15. Pronotum, length 125; width 165; posteroangular setae, inner 30, outer 16. Forewing length 650. Antennal segments III – VII length 35, 35, 30, 45, 20.

Male macroptera. Similar to female but paler and smaller (body length 800), with mouth cone less elongate; antennal segment II as pale as segment I; tergite VIII with very reduced ctenidia, posteromarginal comb complete; tergite IX with 4 setae in irregular transverse row; sternites III – VII with transverse glandular area anterior to antecostal ridge(pl. 1E); parameres fringed laterally and aedeagus with row of teeth near apex.

Type material. Holotype ♀ **Australian Capital Territory**, Black Mt, from flowering *Callitris rhomboidea*, 1.xii.2005 (LAM 4763). Paratypes: 7♀♀ 9♂♂ taken with holotype; **A.C.T.**, Black Mt, Australian National Botanic Gardens, 7♀♀ 5♂♂ from *Athrotaxis cupressoides*, 1.xii.2005; Mt Gingera, 16♀♀ from male cones of *Podocarpus lawrencei*, 25.xii.2003 (LAM 4404).

COMMENTS

The variation in body size is remarkable, both between the sexes and between females from the same population. In the vicinity of Canberra, the largest female studied is almost twice as long as the smallest female, and the males are usually only half as long as females. The males have particularly unusual sternal glandular areas that, instead of being in the centre of each sternite as is typical of Thripidae, are in front of each sternal antecostal ridge (pl. 1E). Males from *Callitris* near Dalby in southern Queensland are similar to those of the type series, but males from *Callitris* at two sites in northern and western New South Wales (Narrabri and Mutawindji) have a glandular area only on the third sternite. Females from these sites cannot be distinguished from those of the type series. The males of the New Zealand species, *L. paropsidis*, have not yet been found.

HOST RANGE OF *L. PINOPSIDIS*

Because of the wide geographic range of this species in Australia, and the great variation in size of females within any single sample, the type series is limited to material taken in the vicinity of Canberra. In this area the species has been found in considerable numbers on *Podocarpus lawrencei* on Mt Gingera, on *Callitris rhomboidea* on Black Mt, and on cultivated *Athrotaxis cupressoides* at the Australian National Botanic Gardens. However, apparently identical specimens have been found on *Callitris* species at various sites across New South Wales, at Dalby in southern Queensland, and at Darwin in the Northern Territory. At each of these sites the thrips was found only on *Callitris* trees that were producing pollen, and although different host-plant species

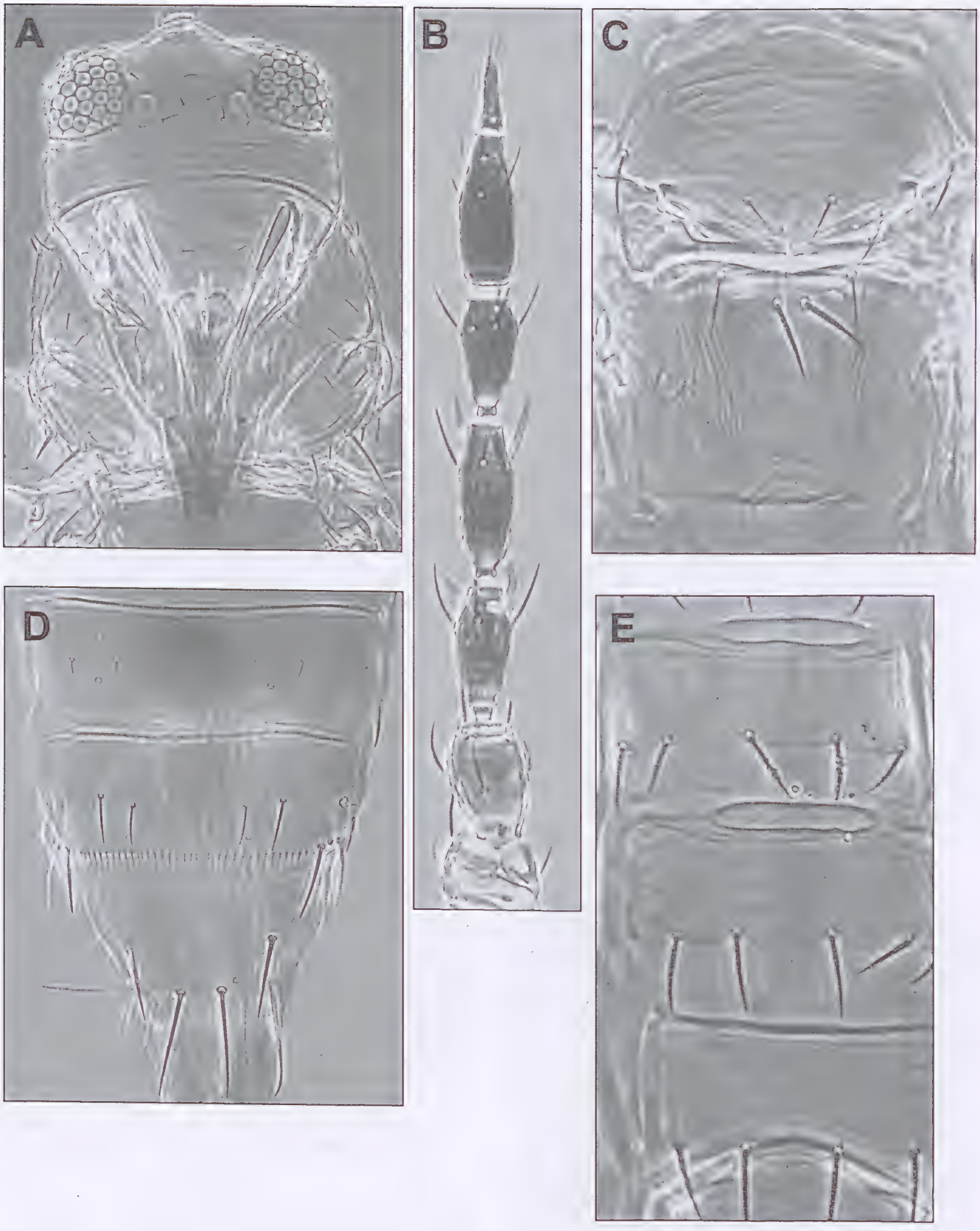

PLATE 1

Lomatothrips pinopsidis. *(A) Head and prothorax; (B) Antenna; (C) meso and metanota; (D) Abdominal tergites VII – X of female; (E) Sternites VI – VIII of male.*

are involved there is no evidence that more than one thrips species is represented.

The three host plant genera of *L. pinopsidis* represent three of the families of the Pinopsida (Cupressaceae, Podocarpaceae and Taxodiaceae). Isolated winged females have been taken on a wide range of other plants around Canberra at various times, not always in the immediate vicinity of *Callitris*, suggesting that the species although host-restricted is behaviourally dispersive. However, it has not been found in the male cones of any of the introduced species of *Pinus*, and thus within the Pinopsida it exhibits some level of host specificity. In this connection it should be noted that the only other Australian species of Thripidae known to be associated with Pinopsida is recorded from two further families (Araucariaceae and Pinaceae). *Pseudanaphothrips araucariae* Mound & Palmer has been found breeding in the male cones of two species of *Araucaria* as well as the cones of two species of *Pinus*. At one locality in Queensland the populations on *Pinus* were so large that they constituted a public nuisance (Mound *et al.* 2002).

ACKNOWLEDGEMENTS

I am grateful to many colleagues for help in the preparation of the information included in this paper, including Dr Alice Wells (Canberra), Dr Nick Martin (Auckland) and Dr Peter Cranston (Davis, California).

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(accepted 3 July 2006)

BENTHIC MACROINVERTEBRATE COMMUNITIES OF HIGH-CONSERVATION VALUE THIRSTY AND LITTLE THIRSTY LAGOONS, CAPE BARREN ISLAND, TASMANIA

by Alastair Hirst, Jane Alpine and Christine Crawford

(with one table and six text-figures)

Hirst, A., Alpine, J. & Crawford, C. 2006 (30.xi): Benthic macroinvertebrate communities of high conservation value Thirsty and Little Thirsty Lagoons, Cape Barren Island, Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 140: 17–23. ISSN 0080-4703. Marine Research Laboratories, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania, Private Bag 49, Hobart, Tasmania 7000, Australia. (AH*, JA, CC). *Author for correspondence.

This study represents the first account of the invertebrate ecology and biology of the estuarine Thirsty and Little Thirsty coastal lagoons on Cape Barren Island, Tasmania. Due to its remoteness, Thirsty Lagoon is one of the most pristine coastal lagoon systems in Tasmania and is, therefore, an important reference point against which to measure future human impacts in coastal lagoons in the Bass Strait islands, and in south-eastern Australia generally. The system comprises two interconnected lagoons. The lower of the two lagoons, Thirsty Lagoon, is connected to the sea by an open channel allowing tidal exchange. This exchange maintains salinities in the lower reaches at or near seawater concentrations. As the basin is shallow, rates of evaporation are high, particularly in summer, elevating salinity levels and resulting in periodic drying-out of sections of the lagoonal system. At the time of our visit in late summer, freshwater input from feeder streams was minimal and there was little tidal exchange between Thirsty and, the upper lagoon, Little Thirsty. As a consequence salinities in Little Thirsty were very high (ca. 60). These coastal lagoons, and one other sampled, supported a low diversity of invertebrate fauna that is typical of coastal lagoons elsewhere in Tasmania. The fauna included marine polychaete worms, molluscs, small crustaceans and high densities of a dipteran larvae in Little Thirsty Lagoon. The fauna found in the lower reaches of Thirsty Lagoon include a number of invertebrate species that are typically marine in origin, while the upper reaches were dominated by species that commonly occur in estuaries elsewhere, albeit in low salinity or brackish waters. Despite very high salinities and periodic evaporation, Little Thirsty and Thirsty lagoons supported high densities of invertebrates that may constitute an important food source for visiting migratory and wading birds.

Key Words: hypersaline, coastal lagoons, benthos, Thirsty Lagoon, Little Thirsty Lagoon, Cape Barren Island.

INTRODUCTION

Cape Barren Island (4473 ha) is a remote island situated off the southern tip of Flinders Island in Bass Strait. Due to its isolated location and small population, large tracts of land, especially on the east coast, are almost entirely free from human impacts. The geology of Cape Barren Island is dominated by granite ridges surrounded by coastal lowlands of unconsolidated sands forming a complex of beach ridges and sand dunes containing many lagoons and swamps. Coastal lagoons are a feature of the eastern coastline of Flinders and Cape Barren islands where sand dunes block drainage to the coast. Rainfall is low, and follows a mediterranean pattern with higher rainfalls in winter than summer. Freshwater catchments are small, so that many of the smaller streams flow only after good rainfalls and therefore freshwater input into these lagoons is episodic. Coastal lagoons on the east coast of Cape Barren Island have special significance and have been listed as both internationally important wetlands (under the Ramsar convention) and as having high estuarine conservation significance (Edgar *et al.* 1999a).

The Thirsty Lagoon system is the largest estuarine system in the Ramsar-listed Cape Barren Island lagoons and is located on the remote east coast of Cape Barren Island (40°24'S, 124°26'E). This lagoon was assigned the highest conservation significance (Class A) under a statewide assessment of the conservation significance of Tasmanian estuaries (Edgar *et al.* 1999a), on the basis of having the most pristine catchment of any of the Bass Strait island estuaries; however, due to its remoteness it was not visited. As a consequence, baseline information on the morphology and biology of this estuarine system is lacking, impeding future planning. In an effort to address these knowledge gaps a visit to Thirsty Lagoon was undertaken in March 2005 with the aim of (1) making direct observations on the morphology of the Thirsty/Little Thirsty Lagoon system; (2) collecting environmental data (salinity and dissolved oxygen concentrations); and (3) sampling benthic macroinvertebrate communities from soft-sediment habitats in the lagoons.

MATERIALS AND METHODS

Description of Lagoons and Sites

Thirsty Lagoon is a shallow coastal lagoon with a permanent opening to the sea. The opening comprises a channel approximately 40 m wide and 1–2 m deep that crosses a significant sand bar at the entrance to the lagoon. At its widest point the lagoon is approximately 1 km across, but less than 0.4 m deep (fig. 1). A number of small creeks feed the lagoon from the coastal dunes to the east and from adjoining heathland to the west. Few of these creeks were flowing at the time of our visit. Thirsty is connected to Little Thirsty Lagoon, directly to the south, via a narrow channel (shown in fig. 1). Little Thirsty Lagoon is a shallow (<15 cm depth), hypersaline lagoon (see Results) that was observed to visibly shrink during the period of this visit (8–10 March 2005), due to evaporation. Because of its small size, salinity may vary greatly in response to rainfall and stream flows – it is fed by a small creek directly to the south (fig. 1). It is conceivable that during winter this lagoon may be brackish or even fresh in character. The tidal connection between these

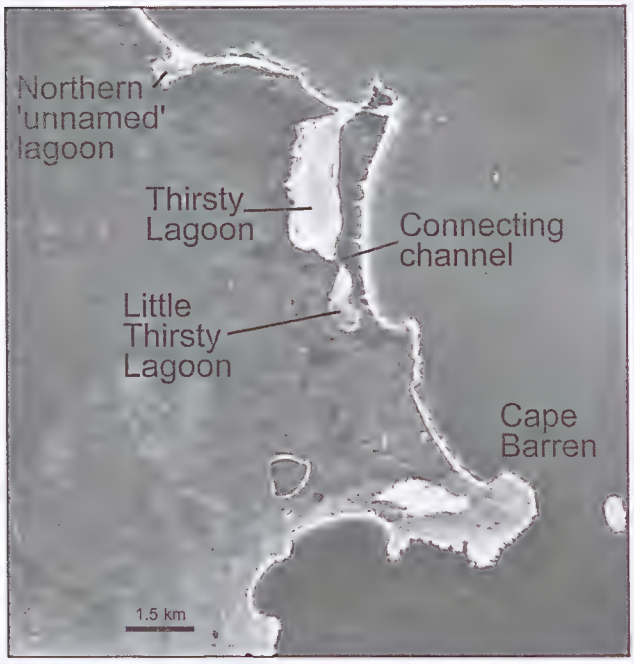

FIG. 1 — Aerial view of Thirsty Lagoon, Little Thirsty Lagoon and a small unnamed coastal lagoon off to the northwest.

two lagoons appears ephemeral and at the time of our visit, tidal inundation from the coast did not reach Little Thirsty Lagoon, leaving this body of water isolated from the lower, Thirsty Lagoon.

A small marine lagoon directly to the northwest of Thirsty Lagoon was also sampled (fig 1). This inlet is unnamed and hereafter we refer to it as the 'Northern Lagoon'. An opening to the sea is maintained only at high tide when the rising waters spill over a sand bar at the entrance to the inlet. Two small creeks, visible on the aerial photograph, feed a lagoon that in places reached 1.0 m in depth. At the time of our visit the flow of freshwater into the Northern Lagoon was clearly greater than to Thirsty and Little Thirsty lagoons.

FIELD METHODS

Salinity and dissolved oxygen measurements were made and benthic invertebrate communities sampled at eleven sites throughout Thirsty, Little Thirsty and the Northern lagoons during a visit to the area during 8–10 March 2005. Sites were chosen to represent conditions throughout the geographic extent of the lagoons (fig. 2). Four sites were sampled from Thirsty Lagoon, two at either end of the connecting channel, three sites in Little Thirsty Lagoon and two sites in the Northern Lagoon, one in the channel just behind the sandbar and the other in the lagoon proper adjacent to a creek entrance. The position of each site was marked in the field using GPS.

Sampling of the benthic invertebrate fauna was undertaken as close as possible to low tide using a 15-cm-diameter PVC sediment corer inserted to a depth of 10 cm. Four replicate cores were collected at each site from shallow subtidal sediments, adjacent to the low water mark (except for site 3 which was located in the middle of Thirsty Lagoon). Sediment cores were sieved in the field through a 1.0 mm mesh sieve and the portion retained on the sieve fixed in 10% formalin-seawater solution. Salinity and dissolved oxygen concentrations were measured at each site using WTW conductivity/temperature and dissolved oxygen meters. Dissolved oxygen was measured in mg O_2 per litre of water (mg/L), whilst salinity measurements are expressed as dimensionless practical salinity units (UNESCO 1985). All fieldwork was done on foot, precluding more extensive sampling of the area.

Samples were sorted in the lab under a binocular microscope. Invertebrate taxa, where possible, were identified to species and counted. Invertebrate specimens have been lodged with the Tasmanian Museum and Art Gallery, Hobart. Species and total abundances were expressed as numbers per m^2 based on the mean of the four replicate samples collected per site. Abiotic and biological data were superimposed onto maps of the lagoons using ArcGIS v9 GIS software.

RESULTS

Environmental Conditions

Sites displayed a clear gradient of increasing salinity from the marine entrance of Thirsty Lagoon to the upper reaches of Little Thirsty Lagoon (fig. 3). Whilst salinities in the lower reaches of Thirsty Lagoon were 36, corresponding with marine conditions, hypersaline conditions prevail in the shallow waters of Little Thirsty Lagoon and all sites recorded salinities in excess of 60. The elevated salinity observed on this visit was probably the result of evaporation in the absence of any significant freshwater input from feeder creeks and/or the input of tidal waters from Thirsty Lagoon. It is unclear how long these conditions prevail, but hypersaline conditions may persist over much of the summer months interrupted only by significant rainfall or unusually high tides. Based on our observations it is also conceivable that this lagoon dries out entirely and is, in effect, an evaporative basin. High salinities, nevertheless, imply irregular connection between Thirsty and Little Thirsty and the presence of wrack (i.e., kelp and other seaweeds originating from the open coast) in Little Thirsty supports the view that these two bodies are at least temporarily connected throughout the year.

Waters within the lagoons were generally well oxygenated. With the exception of the connecting channel, dissolved oxygen levels exceed 7.0 mg/L (fig. 4). This is likely to be because the lagoons are extremely shallow precluding stratification and are well mixed by the wind. There was no association between salinity and dissolved oxygen concentrations with dissolved oxygen concentrations towards the mouth only marginally higher (7.9 compared to 7.4 mg/L at the upper L. Thirsty sites).

Invertebrate Communities

Twenty invertebrate taxa were collected from the Cape Barren lagoons during this visit (table 1). The most common taxa were chironomid insect larvae, the gastropods *Batillariella estuarine* (Tate, 1893) and *Ascorhis victoriae* (Tenison Woods, 1878), the bivalve *Arthritica semen* (Menke, 1843) and the polychaete worm *Simplisetia aequisetis* (Augener, 1913). All species collected from Little Thirsty Lagoon and the Northern Lagoon were also found in Thirsty Lagoon. In general, invertebrate species richness declined from Thirsty to Little Thirsty Lagoon, although the latter sites supported comparable numbers of species to the two sites sampled

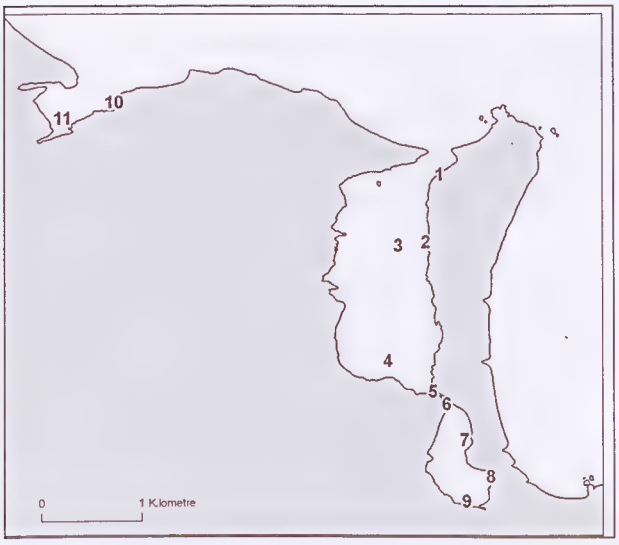

FIG. 2 — Map of the lagoons showing the position of the 11 sites referred to in this study.

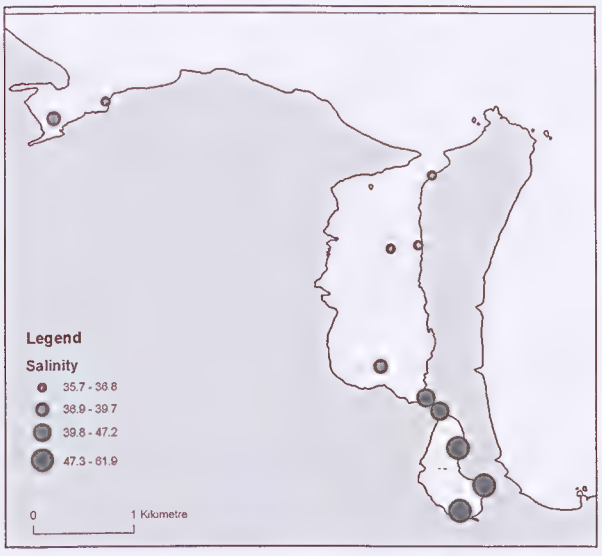

FIG. 3 — Salinity recorded at each of the sites.

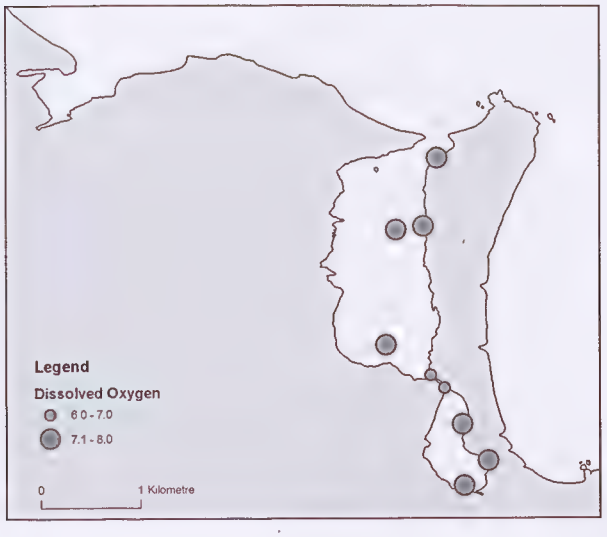

FIG. 4 — Dissolved oxygen concentrations (mg O_2/L) recorded at each of the sites. Note dissolved oxygen measurements were not taken for the Northern Lagoon.

from the Northern Lagoon (fig. 5). No similar pattern was discernable in terms of invertebrate densities between lagoons. The highest densities were recorded in the channel interconnecting the two lagoons (fig. 5), swelled by high abundances of *B. estuarina, A. victoriae, A. semen, S. aequisetis* and the amphipod *Paracorophium* sp.

Distribution and Abundance of Common Invertebrate Species

The gastropod *B. estuarina* was widely distributed throughout the lagoons and was collected at all sites sampled in this study (fig. 6A). It was most abundant in the mid and upper reaches of Thirsty Lagoon including the channel, although still occurred at densities in excess of 500 individuals m^{-2} at site 8 in Little Thirsty Lagoon. By comparison, a number of invertebrate species including the bivalve *Paphies erycinea* (Lamark, 1819) (fig. 6B), the polychaetes worms *Perinereis vallata* (Grube, 1858) (Nereididae) and *Chlymenella* sp. (Maldanidae), the amphipod *Paracalliope* sp. and nemertean worms were primarily restricted to the lower reaches of Thirsty Lagoon (table 1).

Little Thirsty and the interconnecting channel were characterised by high densities of Chironomidae larvae (fig. 6C), but *S. aequisetis* (fig. 6D), *A. semen* (fig. 6E) and *Paracorophium* sp. (fig. 6F) were also abundant at these sites. Chironomid larvae, *S. aequisetis, B. estuarina* and *A. semen* were all found at densities in excess of 150 individuals m^{-2} at sites with salinities in excess of 60. Despite the marine conditions prevalent in the Northern Lagoon, samples collected contained only a restricted fauna comprising eight species in total (table 1). The most abundant species were the gastropods *A. victoria, B. estuarina,* and the polychaete *S. aequisetis.* Chironomid larvae were notably absent from these two sampling sites.

DISCUSSION

Biology of Thirsty Lagoon

Thirsty Lagoon is characteristic of seasonally hypersaline estuaries/coastal lagoons found elsewhere in the world (Largier *et al.* 1997). Cape Barren Island has a mediteranean climate, with dry summers, and the lagoon is fed by a small catchment with streams that flow irregularly and comprises a shallow evaporative basin. The salinity regime in these lagoons may therefore follow a similar pattern to that found among seasonally hypersaline estuaries on the south-west coast of Western Australia (Hearn *et al.* 1994) and the Californian coast (Largier *et al.* 1997) that alternate between classical estuary during winter (net dilutive basin) and hypersaline estuary (net evaporative basin) during the drier, summer months. The separation of Thirsty and Little Thirsty Lagoons is likely to further exacerbate the hypersaline conditions observed in Little Thirsty Lagoon, as the upper basin becomes periodically isolated from the remainder of the system preventing the incursion of tidal waters that may depress overall salinities. The presence of wrack in Little Thirsty, however, supports the view that these two bodies are at least temporarily connected throughout part of the year.

Many of the invertebrate fauna associated with Cape Barren lagoons are common and conspicuous components of estuarine faunas elsewhere in Tasmania (Edgar *et al.* 1999a,b)

TABLE 1
Distribution and mean abundance (no./m²) of invertebrate species collected from Cape Barren lagoons in March 2005

	Thirsty Lagoon						Little Thirsty Lagoon			Northern Lagoon	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
Crustacea											
Paracalliope sp.	58.8	0	2.8	0	1.4	0	0	0	0	0	0
Paracorphium sp.	0	0	28	7	127.4	211.4	4.2	28	29.4	19.6	1.4
Urohaustorius sp.	2.8	0	0	0	0	0	0	0	0	0	0
sphaeromatid isopods	0	7	16.8	11.2	0	0	0	0	0	0	0
Mollusca											
Arthritica semen	0	0	0	14	550.2	378	7	245	0	5.6	28
Ascorhis victoriae	0	0	0	0	92.4	275.8	1.4	8.4	0	33.6	138.6
Batillariella estuarina	5.6	1716.4	331.8	904.4	518	158.2	16.8	358.4	1.4	11.2	105
Coxiella striata	0	0	0	0	1.4	8.4	19.6	2.8	8.4	0	0
Katelysia scalarina	0	0	4.2	0	0	0	0	0	0	0	0
Salinator fragilis	0	2.8	0	29.4	1.4	0	0	0	0	8.4	0
Paphies erycinea	0	131.6	551.6	16.8	0	1.4	0	0	0	0	0
Xenostrobus inconstans	0	0	0	7	0	0	0	0	0	0	0
Polychaeta											
Capitella sp.	1.4	23.8	4.2	8.4	0	5.6	26.6	22.4	26.6	1.4	2.8
Perinereis vallata	0	48.2	11.4	65.3	0	0	1.4	0	0	0	1.4
Simplisetia aequisetis	2.8	58.2	2.8	4.3	110.7	210	1.4	76.6	198.7	18.4	44
Malacoceros sp.	1.4	46.2	0	15.4	0	0	0	0	0	0	0
Clymenella sp.	0	0	79.8	0	0	0	0	0	0	0	0
Scoloplos normalis	0	0	5.6	0	0	0	0	0	0	0	0
Nemertea	0	0	14	0	0	0	0	0	0	0	0
Insecta											
Chironomidae spp.	4.2	21	14	15.4	1229.2	1243	579.6	263.2	509.6	0	0

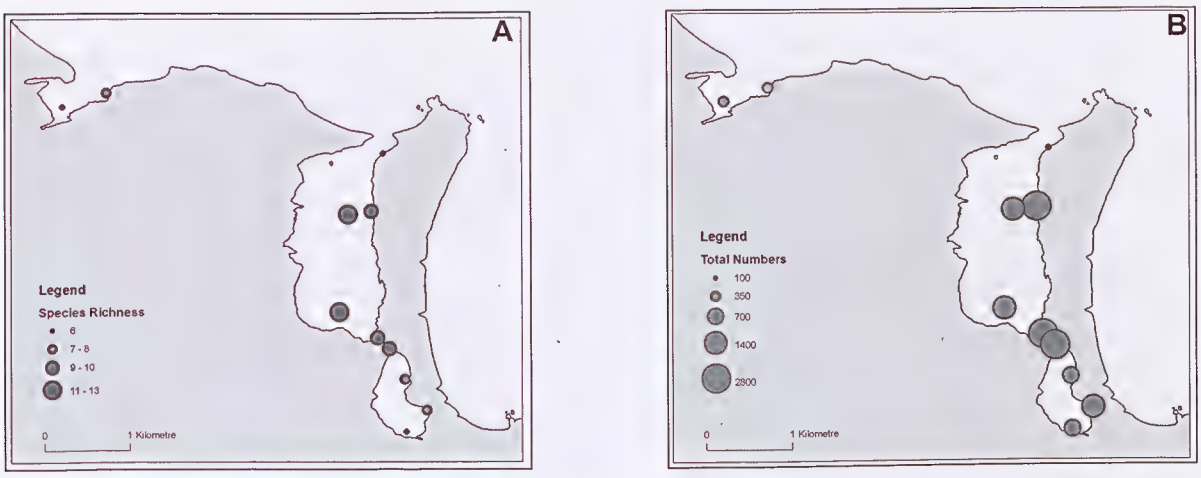

FIG. 5 — (A) Invertebrate species richness and (B) faunal densities (no. individuals m^{-2}) recorded at each of the sites.

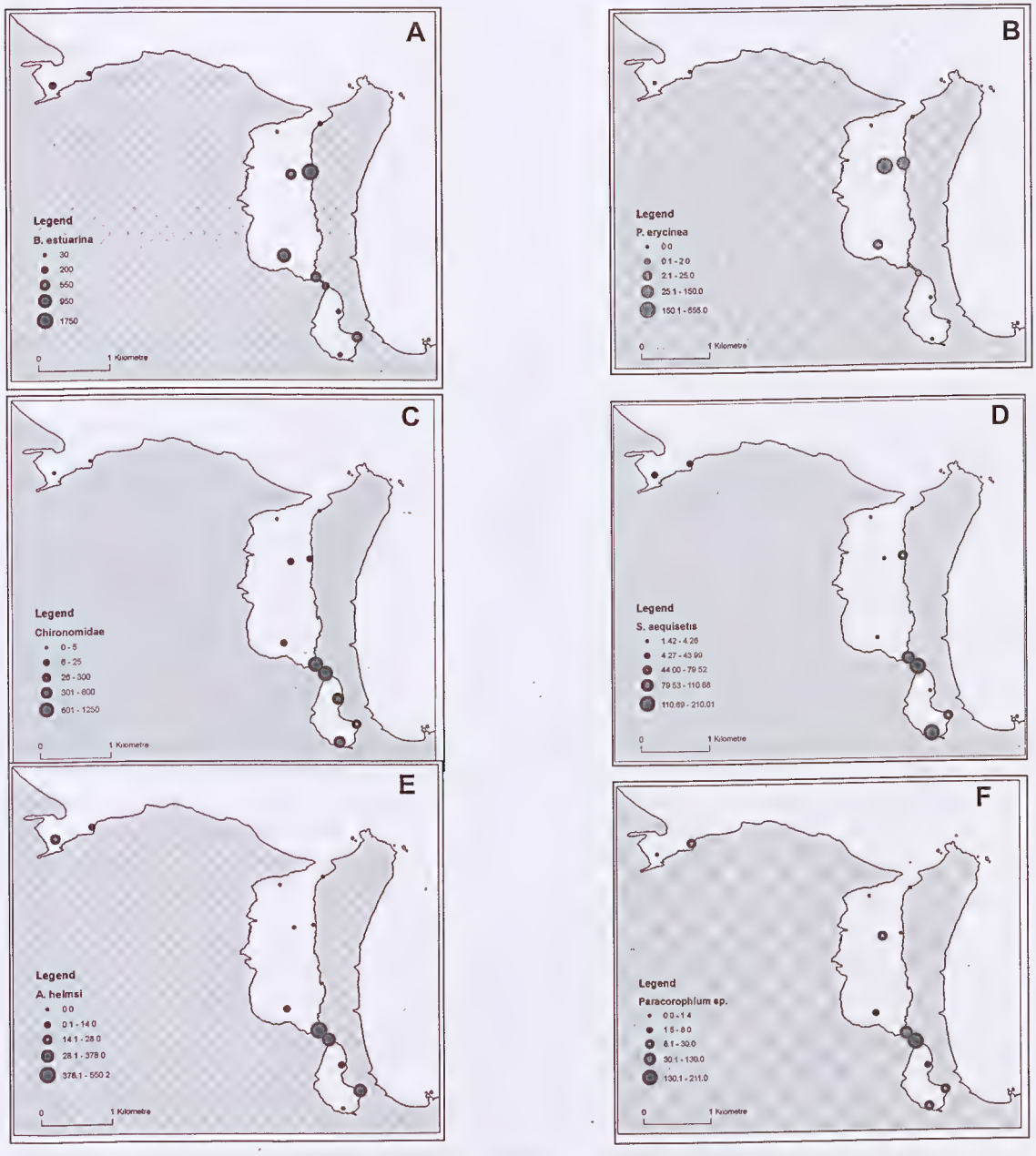

FIG. 6 — Densities (no. individuals m^{-2}) of the (A) gastropod Batillariella esturarina*; (B) bivalve* Paphies erycinea*; (C) Chironomid insect larvae; (D) polychaete worm* Simplisetia aequisetis*; (E) bivalve* Arthritica semen*; and (F) amphipod* Paracorophium *sp. at each site.*

and southeastern Australia (Hirst 2004). In particular *A. victoriae*, *B. estuarina*, *Paracorophium* sp. and *S. aquisetis* have widespread distributions. Whilst coastal lagoons do not support distinct faunal communities (Barnes 1994), they generally support impoverished faunas in comparison to other estuarine systems (Barnes 1994, Edgar *et al.* 1999b). We collected only 20 species on this visit, whilst a similar level of sampling in meso-tidal river estuaries in north-west Tasmania, one month later, produced about 50 species per estuary (Hirst *et al.* 2005). The low species richness of coastal lagoons has been attributed to their smaller size, greater uniformity of habitats, isolation (or at least partial isolation) from the sea through the formation of a barrier at the entrance limiting the recruitment of species with marine life-histories or affinities (Barnes 1994) and greater environmental extremes (e.g., salinity, anoxia) (Barnes 1994).

In terms of the species composition of the fauna, Thirsty Lagoon most resembles Cameron Inlet, a barred coastal lagoon on the east coast of Flinders Island with recorded summer salinities exceeding 50 (Edgar *et al.* 1999a). Thirsty Lagoon, by comparison, had a substantial marine opening allowing significant tidal exchange at the time of our visit. This facilitated the influx and survival of species with greater marine affinities such as the polychaetes *Perinereis vallata* and *Clymenella* sp. (Maldanidae) and the bivalve *Paphies erycinea* (Edgar *et al.* 1999b). In general, these species were restricted to the lower reaches of Thirsty Lagoon where salinities were close to marine (~ 36). In comparison, Little Thirsty and the upper reaches of Thirsty Lagoon are dominated by a range of invertebrate species that are typically confined to estuaries. These include *S. aequisetis*, *Paracorophium* sp. and *A. victoriae* (Edgar *et al.* 1999b), whilst the chironomid larvae are often typical of the brackish upper reaches of estuaries (Hirst *et al.* 2005). *S. aequisetis* and *Paracorophium* sp. are usually associated with the upper reaches of estuaries where salinities are typically diluted by freshwater input, but are capable of tolerating a wide range of salinities (Edgar *et al.* 1999b). Both are widely distributed throughout the Cape Barren lagoons.

Hypersalinity is a common phenomenon in coastal lagoons in Brazil (da Silva *et al.* 2005) and Mexico (Vega-Cendejas & de Santillana 2004) – where it is more or less a permanent condition – and California (Largier *et al.* 1997) and south-western Western Australia (Hearn *et al.* 1994) where it is linked to seasonal changes in net freshwater input and evaporation Research has focused on documenting changes in structure from marine (generally adjacent to the mouth) to hypersaline regions of coastal lagoons, rather than following seasonal changes in hypersalinity. In general these studies found that the species richness of fish (Vega-Cendejas & de Santillana 2004) and benthic macroinvertebrate (da Silva *et al.* 2005) assemblages declined with increasing salinity and that hypersaline regions supported a restricted fauna of estuarine specialists. Unlike hypersaline coastal lagoons in Brazil and Mexico, where high salinity conditions remain throughout the year, salinities in the Thirsty Lagoon system are likely to vary considerably (although data are lacking at this point). The invertebrate assemblages in Little Thirsty Lagoon will, therefore, need to tolerate not just high, but also possibly very low, ambient salinities and dramatic changes to salinity over potentially very short time-frames. Typically the species found in Little Thirsty Lagoon are associated with low salinities indicative of the upper regions of estuarine ecosystems (Hirst 2004). The same physiological adaptations that allow estuarine species to tolerate low and changing salinities presumably also pre-adapt them to high salinities, although the upper limits of such tolerances are unknown (Edgar *et al.* 1999b).

The other characteristic that makes many of the species found in Little Thirsty Lagoon suited to life in a periodically isolated, hypersaline coastal lagoon is the possession of a direct-developing life-history. Juvenile animals hatch directly from the brood-pouch of the amphipod *Paracorophium* sp. and from embryo tubes constructed by the polychaete *S. aequisetis* (Wilson 2000) rather than arriving from the plankton. Similarly, the most abundant element of the Little Thirsty fauna, the chironomid larvae, hatch from eggs laid by the mobile (i.e., aerial), adult chironomid (midge) in the shallow lagoon waters. Recruitment of these species is not reliant upon the arrival of larvae from the plankton, as is the case for many other marine invertebrates, and consequently these populations are largely self-replenishing. This is critical in a system which is episodically disconnected from the open sea and which may undergo periodic contraction due to evaporation.

We suggest on the basis of this survey, and surveys carried-out by Edgar *et al.* (1999a) as part of a broad-scale survey of Tasmanian estuaries, that there is no specific hypersaline estuarine-fauna, only a fauna adapted to highly variable salinities indicative of the mid and upper regions of estuaries generally. In part, this is because hypersaline conditions are likely to be an ephemeral, rather than a permanent feature of coastal lagoons in southeastern Australia.

Conservation Significance of Thirsty Lagoon

Thirsty and Little Thirsty lagoons comprise extensive areas of intertidal and shallow subtidal sediments that form important feeding habitats for visiting migratory birds, chiefly waders. Up to 25000 migratory waders are believed to come to Tasmania every year during the summer months, many of them to the Furneaux group of islands. Flocks of up to 4000 migratory waders have been observed on Logans Lagoon and Cameron Inlet, Flinders Island (Edgecombe 1986). Flinders and Cape Barren Island also represent convenient stopping-off points for migratory birds moving to and from south-eastern Tasmania on their migratory journeys. Despite high salinities, and evidence of periodic evaporation and drying-out, these lagoons still supported high densities of macroinvertebrates that are commonly found among the diets of wading birds (e.g., bivalves, worms and crustaceans; Dann 1987).

As Thirsty Lagoon was not visited in a statewide assessment of the conservation significance of Tasmanian estuaries, but nevertheless assigned the highest conservation significance, Edgar *et al.* (1999a) suggested that a field survey was required to confirm that the estuary had been placed in the appropriate estuarine group (i.e., coastal lagoon), and if possible should include sampling of the biota of the estuary (invertebrates, fish). Thirsty Lagoon is typical of coastal lagoons on the east coast of Flinders Island. It is very shallow with water depths <0.5 m, receives minimal and/or episodic freshwater input from feeder streams and is subject to highly elevated salinities particularly in the upper reaches. Like Logans Lagoon and Camerons Inlet (Edgar *et al.* 1999a), sections of Thirsty Lagoon appear to periodically evaporate exposing intertidal sand flats during the summer months. Thirsty Lagoon, however, differs from these two coastal lagoons by having a significant opening

to the sea allowing tidal exchange between the open coast and the lagoon – potentially ameliorating evaporation and depressing salinities in its lower sections (i.e., likely to remain closer to marine conditions). We therefore support Edgar *et al.*'s (1999a) conservation assessment of this estuary as it remains one of the few coastal lagoons in Tasmania that is situated within a catchment that is almost entirely free of human impacts. This is important because coastal lagoon systems tend to be susceptible to human impacts because contaminants are more likely to accumulate within the system due to limited tidal exchange (Webster & Harris 2004), requiring more careful management than other estuarine systems.

Acknowledgements

We would like to thank R. Mount (TAFI) for creating the GIS Maps, and R. Wilson (Museum Victoria) and L. Turner (Tasmania Museum and Art Gallery) for help with identification of invertebrates, and G. Edgar for comments on a previous version of the manuscript. The visit to this region was funded by NHT Priority Action Project: "NRM for isolated Communities: building the capacity of aboriginal islanders to manage their own natural resources". We also thank Renee Lowry, NRM Facilitator for the Furneaux region, for organising and coordinating the trip to Cape Barren Island.

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(accepted 3 July 2006)

A SURVEY FOR THE PRESENCE OF THE AMPHIBIAN CHYTRID FUNGUS (*BATRACHOCHYTRIUM DENDROBATIDIS*) IN TASMANIA

by David Obendorf and Alexander Dalton

(with one plate, one text-figure and one table)

Obendorf, D. & Dalton, A. 2006 (30:xi) A survey for the presence of the amphibian chytrid fungus (*Batrachochytrium dendrobatidis*) in Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 140: 25–29. ISSN 0080-4703. 7 Bonnington Road, West Hobart, Tasmania 7000, Australia (DLO*, AD). *Author for correspondence.

A survey confirmed the presence of the amphibian chytrid fungus, *Batrachochytrium dendrobatidis* in a number of frog habitats close to major cities and towns across Tasmania.The detection of chytrid infection in some remote wetlands at high altitude locations on the Tasmanian Central Plateau is of particular concern. The likely presence of chytrid infections was assessed by examining tadpoles for signs of depigmentation, thinning and asymmetry in their keratinized jaw sheaths using a hand lens. Assessing the jaw sheaths of up to 60 tadpoles combined with the application of the Taqman chytrid PCR test was a useful means of detecting the presence of chytridiomycosis at each frog habitat.

Key Words: chytrid, *Batrachochytrium dendrobatiditis*, frogs, disease survey, Tasmania.

INTRODUCTION

Batrachochytrium dendrobatidis is the only chytridiomycete fungus known to affect a vertebrate. This fungus completes its life cycle in the skin of amphibians, utilising keratin as a protein substrate (Powell 1993, Berger *et al.* 1998). Over the course of the past 40 or 50 years this organism has managed to enter, establish and spread on to every continent (except Asia) where amphibians exist (Daszak *et al.*1999, 2003, Stewart *et al.* 2004, Weldon *et al.* 2004). Insidiously the disease – chytridiomycosis – has become the agent of a global pandemic in amphibian populations. Several frog species are now believed to be extinct including six species in Australia (Anon 2005) as a direct result of the entry and establishment of this fungus into local ecologies (Lawrence 1996, Daszak *et al.* 2003).

The movement of frogs with trade produce, particularly bananas, is well recognised (McDonald & Speare 2000, O'Dwyer *et al.* 2000). It has been hypothesized that the eventual escape or release of these frogs into local wetlands may be a probable means for the establishment of this pathogen in local populations of frogs (Hardman 2001, Obendorf 2005). The amphibian chytrid infection is now recognised as one of the major threatening processes causing the decline of frogs and salamanders across the planet (Anon 2006) and chytrid fungus, *B. dendrobatidis* is now listed as a key threatening process under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999.*

Tasmania was one region in Australia that had not reported chytrid (*Bd*) infection in its local frog populations, although there has been evidence of declines in the range and abundance of some species of frog in Tasmania that are susceptible to this infection (Anon 2006). Therefore the Central North Field Naturalists Inc. wished to investigate the cause of frog declines in Tasmania with particular focus on developing a practical field survey method and trialling a new DNA gene probe test for the presence of *Bd* in tadpoles at various frog habitats.

This paper describes the field and diagnostic methods applied to the detection of this cryptic pathogen in a part of Australia where the disease was suspected to occur but had not previously been recognised. An important aim of the Tasmanian *Bd* survey was to trial the effectiveness of these methods so as to support other community groups across Australia in conducting baseline and follow-up monitoring surveys for *Bd* infection in frog populations.

MATERIALS AND METHODS

During the spring and summer of 2005–06 the amphibian research group of the Central North Field Naturalists Inc. (CNFN) conducted a survey of frog habitats for the presence of chytridiomycosis. The survey relied on the use of a visual assessment of keratinized mouthparts of tadpoles, as a preliminary field assessment tool (Fellers *et al.* 2001) and the use of a highly sensitive and specific gene probe test (Boyle *et al.* 2004) to detect *Bd* in samples collected from tadpoles. Details of the full survey methods and the techniques used in the Tasmanian survey are outlined in Obendorf (2005).

Field Surveys

Prior to commencing the study, a *Bd* risk assessment was prepared for Tasmania and its frog fauna. This assessment covered issues such as the number of frog species at a survey site, potential susceptibility of the species present to *Bd* infection and the location of the frog habitat. All field surveys were conducted in accordance with a hygiene protocol for the control of disease in frogs (Anon 2001a, Speare *et al.* 2005).

Equipment (dip-nets, buckets, waders, gumboots and in-contact survey equipment) was appropriately sterilised using effective biocides after each survey. Only one survey was undertaken per day so that all equipment could be adequately decontaminated and dried before re-use. At particular frog habitats where there were frog species deemed to have high susceptibility to *Bd*, additional hygiene precautions were

taken (e.g., the use of new dip-nets). These sites included locations remote from human habitation or human activities such as fishing, vehicle access or walking tracks.

Up to 60 tadpoles per site (mean = 35, range 13–60; no. of sites = 56) were examined in the field surveys. *Bd*-infected tadpoles can be provisionally identified by looking at their pigmented jaw sheaths and tooth rows using a hand lens (x10–12 magnification); bright natural illumination is necessary. Chytridiomycosis-induced mouthpart depigmentation was categorised as obvious areas of white beginning at the base of the normally black jaw sheaths causing the sheaths to appear thinner than normal or to show segmental loss of black pigmentation through a section of the sheath.

Each tadpole was assessed according to the following grading: 0 - normal jaw sheaths; 1 - thinning or asymmetry in any jaw sheath; 2 - obvious segmental depigmentation in any jaw sheath; 3 - substantial depigmentation or complete depigmentation in any jaw sheath. For the purposes of assessing the diagnostic effectiveness of this field survey method, the gradings from both the anterior (AJS) and posterior jaw sheath (PSJ) from each tadpole were recorded at each survey site (pl. 1.). The developmental stage of assessed tadpoles was required to be between Gosner stages 26 and 39 (Gosner 1960, Anstis 2002) because at stages less than 26, tadpoles are too small for manual handling and at stages greater than 39 tadpole mouthparts undergo changes as a result of metamorphosis. To minimise the chances that any observed jaw sheath depigmentation was not caused by cold water or freezing temperatures (Rachowicz 2002), cold climate sites were surveyed during the summer months.

A putative determination of *Bd* status was made if at least one tadpole with a total grading score of 2 or above was recorded at a survey site. Although *Bd* infection leads to depigmentation and changes to the teeth in the tooth rows, these changes were not included in the assessment as physical damage or loss of these delicate structures can be incorrectly ascribed to *Bd* infection whereas the extreme jaw sheath changes (gradings 2 and 3) when present are more likely to be attributable to *Bd* infection. Field assessors identified the tadpoles to species; graded each jaw sheath and assessed the Gosner development stage of each tadpole; these findings were recorded on field sheets by another surveyor. For details on the identification of Tasmanian frog species at the tadpole stage and Gosner development stages, see Anstis (2002) and Littlejohn (2003).

Inspection of jaw sheaths of tadpoles involves gently placing a tadpole on a moistened hand with the tadpole's head pointing toward the fingertips. By arranging the fingers such that the index and third finger slightly overlap the second finger, a tadpole can be carefully held and where necessary a small amount of pressure applied to the ventral body will encourage the jaw sheath to part for full examination. The hand lens under ambient light condition is sufficient to examine the tadpoles and grade the jaw sheaths. Considerable care must be taken in handling tadpoles and assessment should be done as quickly as possible so that tadpoles are out of water for the minimum time.

Laboratory Diagnostic Tests

The highly sensitive PCR amplification gene-probe was used as the definitive diagnostic test to diagnose chytridiomycosis – the Taqman PCR *Bd* assay (Boyle *et al.* 2004). During our field surveys we assessed a range of sampling techniques initially involving the sacrifice of up to six tadpoles per site for testing (Obendorf 2005). Selected tadpoles were killed using an overdose of the anaesthetic benzocaine. Using sterile technique to minimise any DNA contamination between samples, the oral disc of each sampled tadpole was excised and separately placed onto a filter paper. Filter papers were dried and labelled and separately stored in small zip-lock bags (Obendorf 2005). The filter paper samples were then tested using the Taqman PCR *Bd* assay.

In the latter stages of the survey, the CNFN amphibian survey group validated the use of a non-lethal sampling technique involving gently touching a fine tip swab onto the oral discs of tadpoles (MW100 fine tip swab - Medical Wire Equipment UK). This process, if applied with care, results in no permanent damage to tadpoles allowing all animals to be returned to their habitat (A. Dalton, unpublished data). The swabs were then dried in a low temperature desiccator to minimise DNA degradation prior to batch submission to the testing laboratory.

Care was taken not to cross-contaminate samples as only a small amount of contamination can lead to false positive results. The comparative effectiveness of the live swabbing

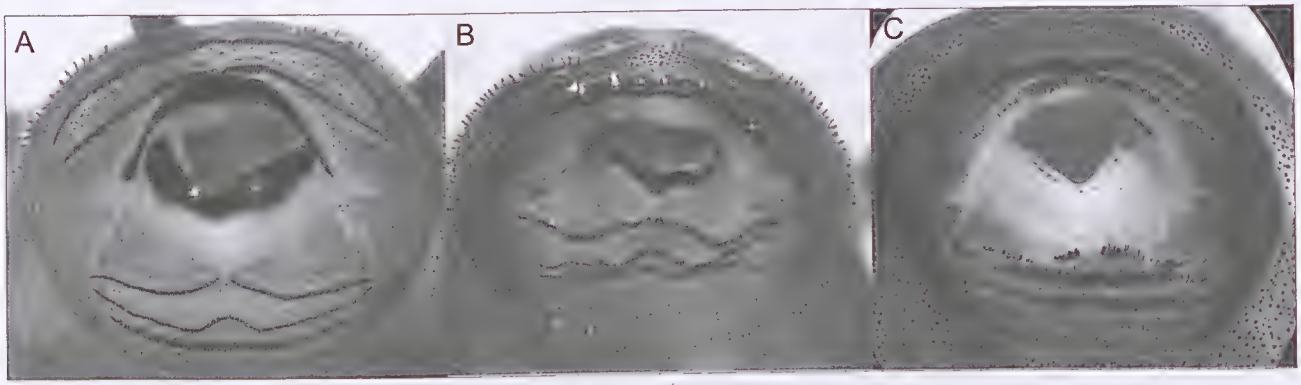

PLATE 1

Oral discs of Brown Tree Frog (Litoria ewingii) *tadpoles with grading scores (AJS – anterior jaw sheath, PJS –posterior jaw sheath). (A) Normal mouthparts; total score = 0. (B) Thinning and segmentation with almost complete loss of AJS (3) and thinning and asymmetry in PJS (1); total score = 4. (C) Almost complete loss of both jaw sheaths AJS (3), PJS (3) with segmental loss of tooth rows; total score = 6.*

method versus the necropsy oral disc sampling method will be reported elsewhere.

The CSIRO Australian Animal Health Laboratory in Geelong undertook the real-time Taqman PCR on the samples for the presence of amphibian *Bd* (Boyle *et al.* 2004).

The findings from the tadpole mouth part gradings at each survey site were compared to the results obtained from the laboratory PCR tests taken from the selected sub-sample of tadpoles from the same survey site.

RESULTS

Survey Findings

Batrachochytrium dendrobatidis was confirmed to be present in 33 of 56 Tasmanian survey sites. We compared the visual assessment method based on the presence of one or more tadpoles showing jaw sheath changes ≥ grading 2 and the results of the Taqman PCR test results from tadpoles sampled from the same site (table 1).

At 25 of 26 sites where one or more tadpoles had jaw sheath changes ≥ 2, the site was confirmed to be *Bd* positive by the PCR gene probe. At one of 26 sites (4%) where one or more tadpoles had jaw sheath changes ≥ 2, the *Bd* PCR gene probe was negative. At 22 of 30 sites (73%) where no tadpoles showed any visual jaw sheath abnormalities. a sub-sample of up to six tadpoles returned *Bd* negative results by the PCR gene probe. At eight of 30 sites (27%) where no abnormal tadpoles were detected, a sub-sample of up to six tadpoles was *Bd* PCR gene probe positive. The status of the Walls of Jerusalem site is designated "probable chytrid positive" because only a small number of *Crinia* spp. tadpoles (13) was examined and the testing laboratory deemed the zoospore DNA replication to be low; they classified the PCR test result "indeterminate".

The conclusions drawn from this survey method are that where a moderate to high number of tadpoles show typical grade 2 to 6 jaw sheath abnormalities (>30% of all tadpoles), there is a very strong likelihood that the surveyed frog habitat is *Bd*-infectious.

Using the *Bd* PCR gene probe as the definitive test for *Bd* presence at a frog habitat, a field survey of up to 60 tadpoles between Gosner stages 26 to 39 was successful at 84% of the sites surveyed. At only one survey site did the PCR probe not confirm the presence of *Bd* whereas the field survey suggested a putative positive result.

Using the *Bd* PCR test result as the definitive test for *Bd* presence or absence, the number of survey sites designated as *Bd*-positive increased from 25 to 33 (n=56).

Relying only on the field survey assessments is not recommended. If the visual assessment of the jaw sheaths in tadpoles is used as the only confirmatory test for the presence of *Bd* infection, it has the potential to occasionally give a false positive result (4% or 1 of 26 surveys) or a false negative result (27% or eight of 30 surveys). Natural or traumatic loss of a single jaw sheath, in the absence of any other abnormalities in the remaining jaw sheath and tooth rows, could be graded incorrectly. In addition, surveying tadpoles in advanced Gosner stages can also increase the likelihood of classifying the physiological loss of a jaw sheath incorrectly as a grade 3 change. An absence of jaw sheath changes in any tadpoles at a survey site has the potential to more frequently suggest that *Bd* infection is not present.

TABLE 1
Visual survey results compared to chytrid PCR results from 56 Tasmanian frog habitats

Chytrid PCR Results	Jaw sheath lesions	No jaw sheath lesions	Total
Positive	25	8	33
Negative	1	22	23
Total	26	30	56

Therefore where no jaw sheath abnormalities are found in any tadpoles at a given wetland, *Bd* PCR testing is always recommended.

CONCLUSIONS

Using the two methods (visual assessments of tadpoles and back-up PCR testing) the survey method showed that chytridiomycosis already has gained a wide distribution in Tasmania including several locations around the major cites of Hobart, Burnie, Devonport and Launceston as well as small towns and farming sites such as Dover, Seven Mile Beach, Hawley near Port Sorell and Elizabeth Town. The confirmation of *Bd* at remote sites such as Mother Cummings Plateau and Cradle Mountain National Park, in Tasmania's highlands suggests that the disease has also entered and established itself in remote and high altitude areas of Tasmania (fig. 1). Notably four locations with high frog biodiversity (≥ six species) and with stronghold populations of Green & Gold Frogs were shown to be currently free of *Bd* infection (e.g., Waterhouse Protected Area and Northdown).

The survey results identified at least six species of Tasmanian frog as having *Bd* infections in their tadpole stages. These are the Brown Tree Frog (*Litoria ewingii* Duméril & Bibron, 1841), Green & Gold Frog (*Litoria raniformis* Keferstein, 1867), Southern Banjo Frog (*Limnodynastes dumerilii insularis* Parker, 1940), Spotted Marsh Frog (*Limnodynastes tasmaniensis* Günther, 1858), Common Froglet (*Crinia signifiera* Girard, 1853) and Tasmanian Froglet (*Crinia tasmaniensis* Günther, 1864). *Crinia* spp. tadpoles were particularly difficult to assess visually because of their small body size and the somewhat concealed nature of their jaw sheaths.

DISCUSSION

Visual assessment of the jaw sheaths of tadpoles is a useful method of surveying frog habitats for the presence of *Bd* infection provided that surveyors are trained in distinguishing *Bd*-induced changes in the jaw sheaths from natural damage or physiological changes with aging (Anstis 2002). The principal benefit of adopting this survey method for detecting *Bd* infection was the relative ease in catching tadpoles compared to adult and metamorphling frogs. Although aspects of the epizootiology of chytridiomycosis in frog populations are still unclear, we believe this methodology can be used to quickly assess the presence or absence of *Bd* infection. This is particularly relevant in wetlands or bioregions experiencing declines in the abundance and diversity of frog species and

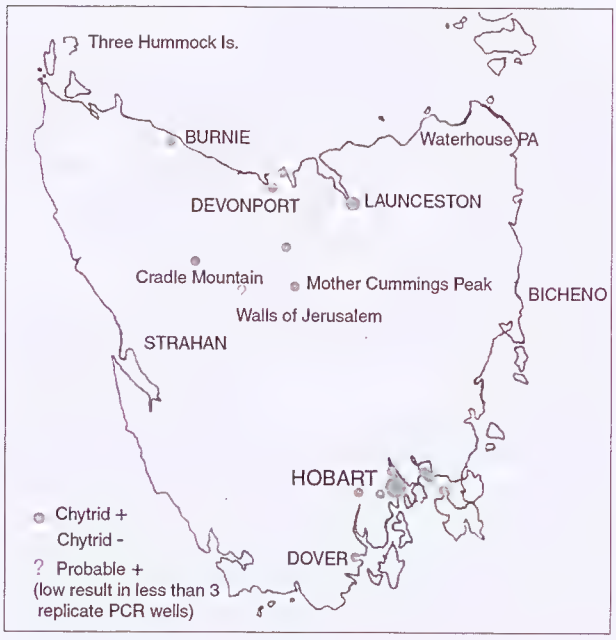

FIG. 1 – Tasmanian chytrid survey sites. Large dots designate ≥3 survey sites within 10 km radius – Hobart 18, Launceston 6, Cradle Mountain 4, Waterhouse 3, Three Hummock Island 3.

where other threatening processes have been discounted. As a preliminary test, the field survey is more accurate in determining the presence of *Bd* infection. The PCR gene probe test is, however, the definitive test for confirmation. At sites where there is evidence of frog declines or actual mortalities, samples from tadpoles or frogs for *Bd*-PCR testing are recommended.

The use of fine-tipped swabs as the method for collecting laboratory samples has now superseded the need to extract the keratinized mouth parts from euthanased tadpoles. Swabbing allows the mouth parts of live tadpoles to be undertaken at the site of the field surveys without loss of life. Use of swabs also considerably reduces the potential problems of DNA cross-contamination. Field surveys of tadpoles can be undertaken from early spring to late autumn.

Bd infection was detected in a number of frog habitats close to the major cities and towns across Tasmania. Stronghold establishment of introduced species in the vicinity of human habitation is consistent with the hypothesis that mainland species of frogs entering with imported fresh produce (especially bananas and horticultural produce such as potted plants) are the most likely source for the establishment of chytridiomycosis in Tasmania (Hardman 2001, Obendorf 2005). Although water containing zoospores of *B. dendrobatidis* and other aquatic material carrying zoosporangia will survive for three to four weeks (Johnson & Speare 2003), the ability of this fungus to successfully survive and spread in the environment in the absence of an amphibian host is unclear. Once *Bd* has entered and established in a new location — in this case Tasmania — subsequent spread may occur by a variety of natural and anthropogenic means.

We believe that the amphibian *Bd* fungus has been in Tasmania for more than two decades. A multiple frog mortality incident in Tasmania in 1993 was recently confirmed to be due to chytridiomycosis (Obendorf 2005). Across its Australian range, the Green & Gold Frog (*Litoria raniformis*) has experienced dramatic declines especially in its inland habitats. This species is also recognised as being particularly susceptible to *Bd* infection (Anon 2006). In Tasmania *L. raniformis* was considered a common and populous species of frog until the early 1980s (Martin & Littlejohn 1982); however, the species is now listed as vulnerable under the Tasmanian and Commonwealth threatened species legislation. The establishment of chytridiomycosis close to the main Tasmanian cities coincides with the locations where declines in *L. raniformis* abundance were initially reported. It has been argued that the decline in the range and abundance of *L. raniformis* is consistent with the introduction of this exotic pathogen (Obendorf 2005). Some coastal wetlands still retain large populations of *L. raniformis* and there may be specific environmental factors (e.g., salt concentration) at these sites that are unfavourable for the establishment of *B. dendrobatidis* (Anon 2006).

The confirmation of *Bd* infection in *Crinia* spp. tadpoles at remote wetlands on the Central Plateau is of concern. Over the past two decades several species of frog inhabiting high altitude montane regions in southeast Australia have experienced declines in abundance and range and are now the subject of threatened species recovery plans (Antis 2002, Gillespie & Marantelli 2000, Berger *et al.* 2004). Such habitats incorporate the area of occupancy of all three Tasmanian endemic species: Tamanian Froglet (*Crinia tasmaniensis*), Tasmanian Tree Frog (*Litoria burrowsae* Scott, 1942) and Moss Froglet (*Crinia (Bryobatrachus) nimbus* Rounsevell, Ziegeler, Brown, Davies & Littlejohn, 1994). The contraction in the range of the endemic *L. burrowsae* was first recognised by the Central North Field Naturalists in the 1990s (Jim Nelson, pers. comm.); the species was last recorded from its type locality (Cradle Valley) in 1997 (Alex Dudley, pers. comm.).

There is an urgent effort to assess the current distribution and potential impact of this disease on Tasmania's 11 native frog species. *The Threat Abatement Plan for Infection of Amphibians with Chytrid Fungus Resulting in Chytridiomycosis* (2006) notes that frogs from colder, high altitude habitats are particularly susceptible to *Bd* infection. Reported dramatic declines in the abundance and range of *Litoria raniformis* — a State and Commonwealth-listed threatened species — is also of particular concern as chytridiomycosis may be a key threatening process responsible in its decline in Tasmania (Anon 2001b). The ongoing movement of frogs and tadpoles where *Bd* infection is now endemic, in our view, is the greatest risk to the entry, establishment and spread of this significant fungal disease into new amphibian ecologies.

ACKNOWLEDGEMENTS

The authors wish to thank the volunteer surveyors Wade and Lisa Clarkson, Steve Cronin, Bill Flowers, Paul Swiatkowski, Jim Nelson, Debbie Hill and Ron Nagorka; Central North Field Naturalist treasurer, Sarah Lloyd for administering the DEH fund; CSIRO AAHL staff Donna Boyle and Alex Hyatt for *Bd*-PCR testing; the School of Zoology, University of Tasmania for local laboratory support, photographic expertise, field assistance, computer wizardry and fellowship; Dr Andrew Parker, Royal Hobart Hospital, Department of Health & Community Services for photomicrography, Robert Walch, Walch Optics for ongoing support relating to microscopes and field cameras; Martin Harris and Karyl

Michaels, WWF Frogs! Program Coordinator for practical support; Professor Rick Speare, James Cook University and Pearl Symonds of the Gap Creek, SE Queensland frog survey group for ongoing advice and support; Dr Rupert Woods, Australian Wildlife Heath Network for additional funding for *Bd* testing. Research conducted under permit number TFA 04193 issued by the Tasmanian Department of Primary Industries, Water & Environment. Central North Field Naturalists Inc. received funding from the Natural Heritage Trust - Invasive Species Program.

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(accepted 2 October)

RECOLONISATION OF LAGOON OF ISLANDS, TASMANIA, BY *BAUMEA ARTHROPHYLLA:* THE FIRST STEP IN REGENERATION OF A UNIQUE ECOSYSTEM?

by Carolyn J. Maxwell and Peter A. Tyler

(with four plates and three text-figures)

Maxwell, C. J. & Tyler, P. A. 2006 (30:xi): Recolonisation of Lagoon of Islands, Tasmania, by *Baumea arthrophylla*: the first step in regeneration of a unique ecosystem? *Papers and Proceedings of the Royal Society of Tasmania* 140: 31–34. ISSN 0080-4703. School of Life and Environmental Sciences, Deakin University, Warrnambool, Victoria 3280, Australia (CJM, PAT); Environmental Services, Hydro Tasmania, Hobart, Tasmania 7000, Australia (CJM*). *Author for correspondence.

Lagoon of Islands was a unique ecosystem. Damming the lagoon in 1964 caused the decline of the ecosystem, destroying the original vegetation and, eventually, rendering the lagoon eutrophic. While this took place the lagoon was colonised by a macrophyte not previously noticed in the lagoon. In an effort to restore acceptable water quality, restoration of macrophyte cover was encouraged by hydrological manipulation. Recent investigations have revealed that one of the original dominant macrophyte species is recolonising the lagoon, creating an alternative management option for the lagoon.

Key Words: Lagoon of Islands, ecosystem recovery, floating islands, *Baumea arthrophylla*, Tasmania, *Triglochin procera*.

INTRODUCTION

Lagoon of Islands is a small lake [9.17 km² at present water level — the value of 0.89 km² quoted by Tyler (1976a, b) was in error by a factor of 10; average depth 1.3 m] on the Central Plateau of Tasmania. It was once a unique ecosystem. When the lagoon was in its natural condition a cyclical-hydroseral process, unique in mechanism and in participating flora, was enacted upon its surface. The lagoon was covered with a floating mat of intertwined rhizomes of *Baumea arthrophylla* (Nees) Boeckler (formerly *Baumea rubiginosa* (Spreng.) Noeck) and *Chorisandra australis* K. L. Wilson (formerly *C. cymbaria* R.Br.), both members of the Cyperaceae (Wilson 1994). The emergent shoots of the reeds formed a dense cover over the surface of the lagoon. Here and there the mat was colonised by a caespitose sedge, *Carex appressa* R.Br., which in turn, as the sedge clump expanded, was colonised by shrubs and, eventually, trees, forming the eponymous islands. As the biomass of an island increased through accumulation of living and terrestrial plant material, the reed mat was eventually depressed so that a moat formed around the sinking island. The consequent waterlogging led to the death of island flora and the remains of the island accumulated in the resultant pool. The process was described and illustrated by Tyler (1976a, b).

We know of no other example of floating islands produced in this way or by these species though there are reports of floating islands which are formed by partly analogous (but not homologous) processes (Gopal *et al.* 2003, Shimizu 1986, Van Duzer 2004). The fact that one of the colonising shrubs, *Callistemon viridiflorus* (Sims.) D.C., is a Tasmanian endemic species (Curtis 1956, Stones & Curtis 1978) fortifies the uniqueness of Lagoon of Islands.

THE DEMISE OF THE LAGOON OF ISLANDS ECOSYSTEM

In 1964 the lagoon was dammed by the Hydro-Electric Commission (now Hydro Tasmania) with the aim of increasing its ability to provide riparian water and to create a trout fishery. The lagoon became a good trout fishery but was of scant value in fulfilling riparian rights.

After damming, the water level (fig. 1) initially increased but later declined to inadequate values to service riparian demand. Twenty years later, in another attempt to increase

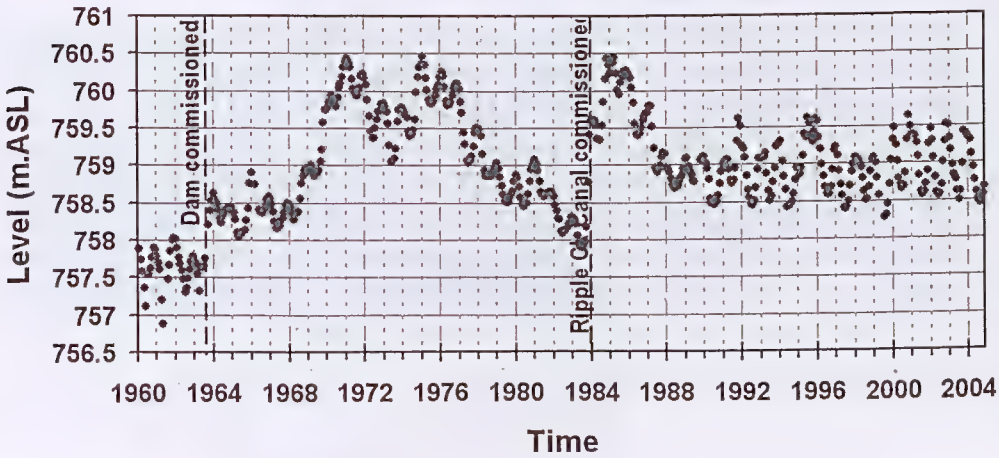

FIG. 1 — Fluctuations in water level between 1961 and 2004 showing the effects of damming and of diversion of Ripple Creek into Lagoon of Islands.

the water available for storage, a canal was constructed to divert the waters of nearby Ripple Creek into the lagoon. With the higher water levels the cover of emergent reeds became ever more sparse and, eventually, the reeds died. The Lagoon of Islands was no longer a swamp with emergent reeds but a lake dotted with the woody remains of island vegetation (Tyler 1976a, b). While these events took place the lagoon was gradually colonised by *Triglochin procera* R.Br. (Juncaginaceae) (the spelling *procerum* is frequently used). As this semi-submerged water plant increased its cover it seemed that it would eventually occupy the entire surface (pl. 1), as the original reeds once did. During 1987 and 1988 the original rhizomatous reed mat broke up and sections of its rotting remains floated to the surface in clumps, strewn along the shore by the wind (pl. 2).

WATER QUALITY ISSUES

The break-up of the reed mat brought the water and sediment strata formerly protected by the mat into circulation in the water column. No nutrient analyses were undertaken but there was the expectation that this would boost the nutrient status of the water column. Whatever the case, water quality declined until it was unfit for irrigation and, concomitantly, the quality of the fishery deteriorated seriously. By 1989 the lagoon was hypereutrophic, with a massive algal bloom (fig. 2). Seen from the air and from space the lagoon shone a brilliant green (see Landsat satellite image in Maxwell 2007). The bloom was not one of blue green algae but, most unusually, almost a monospecific bloom (pl. 3) of the desmid *Staurastrum excavatum* West & West (cf. Thomasson & Tyler 1971).

ATTEMPTS TO RESTORE WATER QUALITY

After the serious decline in water quality observed in 1988, during the period of higher water levels, the Hydro-Electric Commission and Inland Fisheries Commission initiated a number of in-lake and catchment management measures aimed at restoring water quality to acceptable standards for riparian use. These included setting a reduced maximum water level that encouraged the growth of the *Triglochin* in the hope that a dense population of macrophytes would restore equilibrium conditions and favourable water quality (Sanger 1992, 1994). Rea & Ganf (1994a, b) have since shown this was a feasible proposition because the growth of *Triglochin procera* can be directed via a physiological mechanism mediated by water depth. Following the change in operating level some improvement in water quality did occur (Sanger & Bobbi 1992, Sanger *et al.* 1993). However, by 1998 the lagoon was

PLATE 1
Extensive colonisation of Lagoon of Islands by Triglochin procera *(1988).*

PLATE 3
An almost monospecific bloom of Staurastrum excavatum *in Lagoon of Islands, 1988.*

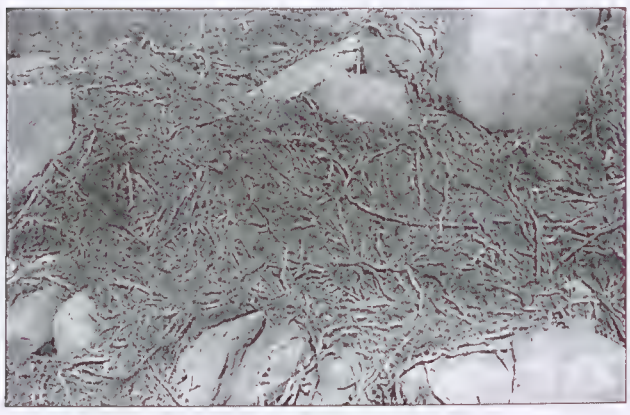

PLATE 2
Decaying rhizomes of Baumea arthrophylla *thrown up on the shoreline as the reed mat broke up (1988).*

PLATE 4
Recolonisation of Lagoon of Islands by Baumea arthrophylla, *2003. The competing macrophyte* Triglochin procera *is in the foreground.*

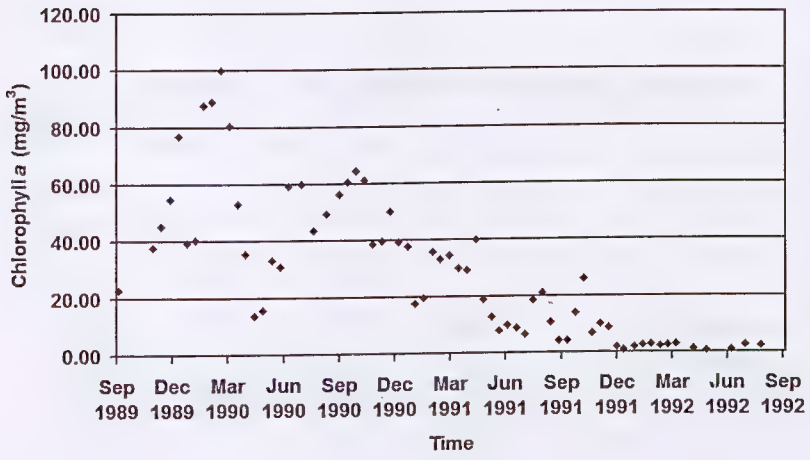

FIG. 2 — Algal biomass (as chlorophyll a) in Lagoon of Islands during the Staurastrum excavatum *bloom, September 1989–September 1992.*

again eutrophic (Maxwell 2007). Renewed investigations into abatement measures were initiated in 2003.

The renewed investigations revealed that *Baumea arthrophylla* has commenced a recolonisation of Lagoon of Islands (pl. 4). Examination of incidental video footage taken over the past decade indicates that recolonisation had commenced at least as early as 1998. At first the regrowth was limited to the western side of the lagoon. A bathymetric survey undertaken in November 2003 failed to locate *Baumea* in the central or eastern portions of the lagoon. However, recent surveys have shown that colonisation by *Baumea* is now widespread, but sporadic (fig. 3), and apparently accelerating.

When the lagoon was in its natural state the emergent reeds that grew all over the lagoon sprouted from a mat of their intertwined rhizomes floating about 1 m below the water surface as a "*schwingmoor*" (Tyler 1976a). It was assumed (Tyler 1976b) that the reeds were rooted in the sediments in the shallow waters of the shoreline and that from this original annulus they had colonised the rest of the lagoon by centripetal spread of their rhizomes, overarching the deeper waters, like a closing iris diaphragm. Such a process, the terrestrialisation of bogs and lakes, is well known in the northern hemisphere (e.g., Tallis 1973) and when the reappearance of *Baumea* was detected in 2003 its restriction to the shallow western rim of the lagoon appeared logical and to be expected. The more recent appearance of clumps of *Baumea* in the deeper, central parts of the lagoon now poses the question of whether the rhizomes are rooted in the sediments or on the remnants of the reed mat. Determination of the circumstances of this sporadic colonisation becomes a priority for the next period

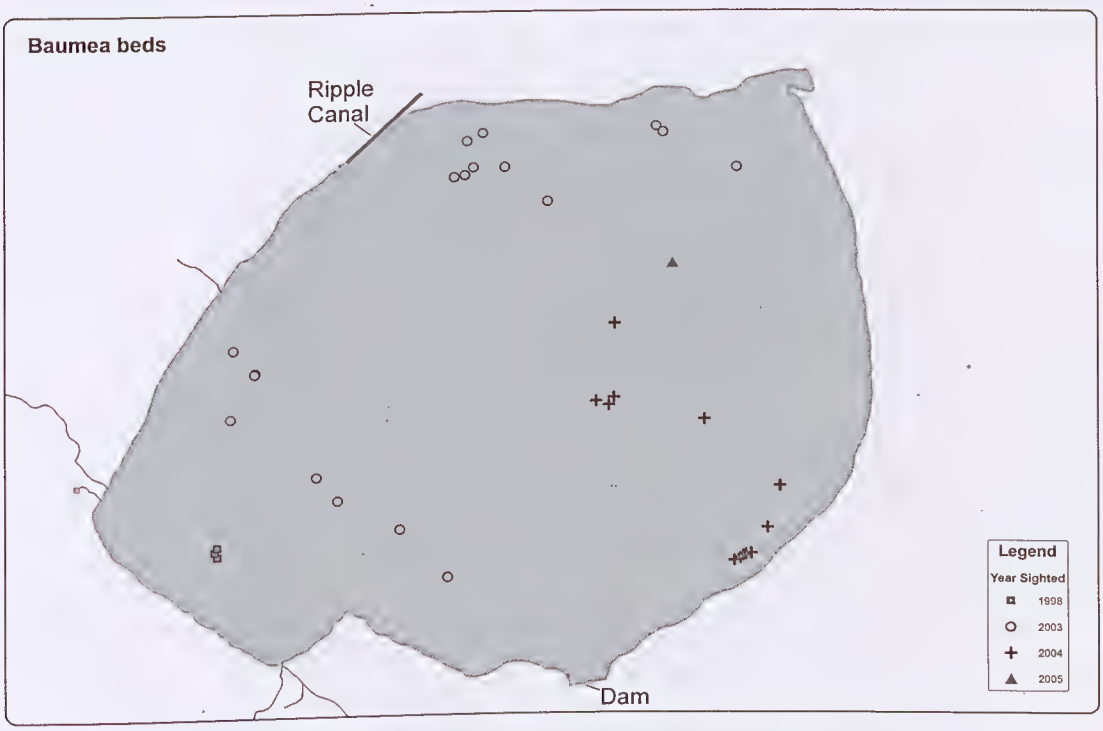

FIG. 3 — Map showing the distribution of Baumea *clumps throughout Lagoon of Islands.*

of low water levels. Continuing investigations suggest that the ecosystem is finely balanced but that the accelerating colonisation by *Baumea* has put the lagoon on a sure path to the desired stability which may be compromised by manipulation that disadvantages *Baumea*.

The reappearance of one element of the original reed bed (*Baumea*) raises the question of whether attempts at restoration of water quality should now be directed towards *Triglochin*, if that were judged to have the greater chance of success, or whether the option of permitting the return of *Baumea* should be taken. The intellectual appeal of the latter is the possibility that the entire hydroseral enactment could once again occur in Lagoon of Islands. For the present, the first step in this direction is the return of *Baumea* after an absence of more than three decades. *Naturam expelles furca, tamen usque recurret* – You may drive out Nature with a pitch fork but she always hastens back (Horace 65–69 BC).

ACKNOWLEDGEMENTS

We thank the late Dennis Morris and Alex Buchanan, both of the Tasmanian Herbarium, for assistance with botanical nomenclature. We thank Marty Jack and the Inland Fisheries Service Biological Consultancy for field assistance. Carolyn Maxwell is funded by a research scholarship from the Australian Research Council and Hydro Tasmania.

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(accepted 2 October 2006)

ECOLOGICAL OBSERVATIONS ON A REMOTE MONTANE OCCURRENCE OF *BEDFORDIA ARBORESCENS* (ASTERACEAE), CAPE BARREN ISLAND, TASMANIA

by Stephen Harris and Eve Lazarus

(with six plates, six text-figures, three tables and one appendix)

Harris, S. & Lazarus, E. 2006 (30:xi): Ecological observations on a remote montane occurrence of *Bedfordia arborescens* (Asteraceae), Cape Barren Island, Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 140: 35–48. ISSN 0080–4703. Biodiversity Conservation Branch, Department of Primary Industries and Water, GPO Box 44, Hobart, Tasmania 7001, Australia (SH*, EL). *Author for correspondence.

Bedfordia arborescens Hochr. is a tree listed under the Tasmanian *Threatened Species Protection Act 1995* and is known in Tasmania only from an outlying population in cloud forest on Mt Munro, Cape Barren Island in the Furneaux Group. While the species is a common component of some rainforest and mixed forest in southeast mainland Australia, the outlying population on Cape Barren Island has apparently been eroded by a high fire frequency over the previous 200 years. The species occupies an ecological zone that is marginal to *Atherosperma moschatum* Labill.-dominated rainforest. Some stands occur adjacent to grasslands separated by a sharp ecological boundary. Even-aged cohorts represent the population structure on the mountain with no evidence of recent regeneration in or adjacent to any particular stand. A range of different aged cohorts occurs within the forest across the mountain. Mt Munro intercepts cloud moisture, resulting in the development of a cloud forest and a steep precipitation gradient between Mt Munro and the nearby coast. The persistence of *B. arborescens* on Mt Munro can be attributed partly to the sharp topographical boundaries that have been reinforced by fire due to the burning frequency on the mountain. The vegetation patterning has responded to frequent anthropogenic fires during the past 200 years. Comparisons are made with subalpine grasslands in New Guinea and elsewhere. Future fire management on Cape Barren Island will be critical to the survival of *B. arborescens* in Tasmania. On the basis of modified IUCN criteria used in Tasmania for listing of threatened species, it is recommended that the status *of B. arborescens* be up-listed from rare to vulnerable.

Key Words: Aboriginal land management, Bass Strait, *Bedfordia arborescens*, Cape Barren Island, conservation status, forest, fire, flora, human impact, Mt Munro, palaeogeography, relict vegetation, temperate cloud forest, threatened species, tree Asteraceae.

INTRODUCTION

Bedfordia arborescens Hochr. or blanketleaf, is in the family Asteraceae, most of which are herbs and shrubs, comprising approximately 25 000 species worldwide. This species is one of the few trees in the family (Heywood 1985).

The taxonomy and distribution of *Bedfordia* species is well known. *B. arborescens* is one of three *Bedfordia* species within Australia (Orchard 2004). *B. salicina* is allopatric with *B. arborescens* (fig. 1). Only *B. linearis* ssp. *linearis* overlaps the range of *B. arborescens* because it has been recorded from Flinders Island (Australian Virtual Herbarium, accessed 27 March 2005). *B. arborescens* is largely a mainland Australian tree while the other two species are endemic in Tasmania. A revision of *Bedfordia* (Orchard 2004) resulted in new subspecific taxa within *B. linearis*. Two key differences between *B. arborescens* and *B. salicina* were defined, namely the ventral leaf hairs on *B. arborescens* occur in two distinct layers in contrast to the single layer in *B. salicina*, and in *B. arborescens* the hairs on the outer layer are floccose and thickened at the base, whereas the hairs on *B. salicina* are clearly appressed or matted and not thickened at the base. *B. arborescens* occurs in wet eucalypt forest, mixed forest, warm temperate rainforest and dry rainforest in southeastern Australia, from Braidwood in New South Wales to southern coastal Victoria (Costermans 1983, Peel 1999). *B. arborescens* in Victorian forests occurs mainly in gullies (Dr D. Ashton, pers. comm.).

B. arborescens was first collected in Tasmania from Mt Munro, the outlying, southernmost extent of its range on 7 October 1988 (voucher specimen: HO114565). Although Robert Brown recorded *Senecio arborescens* on Mt Wellington near Hobart, Vallance *et al.* (2001) claimed this was probably *B. arborescens* Hochr. It is most likely to be *B. salicina*. We note that Brown also recorded *Seneciastrum arborescens* from Mt Wellington, but this is the closely-related (Orchard 2004), large, woody Asteraceae, now known as *Brachyglottis brunonis*. To our knowledge no *B. arborescens* has been collected on Mt Wellington, or at any other Tasmanian location apart from Mt Munro.

On mainland Australia, the tree is common and is not considered to be a threatened species. However, *B. arborescens* was listed as rare in Tasmania due to its localised distribution on Cape Barren Island.

Victorian studies indicate that *B. arborescens* is adapted to periodic fire disturbance. Ashton (1981, 2000a, b) described the relationship between time since last fire, topography, and understorey type, in *Eucalyptus regnans* forests in central Victoria. *B. arborescens* occurs in mixed forest with *N. cunninghamii* and *Atherosperma moschatum* understorey that was last burnt in 1898, and in *E. regnans* forest with an understorey comprising *Bedfordia* that was last burnt in 1926. No studies are known to us that have focused on *B. arborescens*, and certainly no work has been published on the species or its habitat in Tasmania.

Cape Barren Island, comprising 462 square kilometres, is the second largest island in the Furneaux Group, and Mt Munro, rising to 687 m in the northwestern corner of the island, is its highest peak (fig. 2).

The aims of the present study are to gather information that will assist in understanding and managing *B. arborescens*, and to reassess its Tasmanian conservation status. This is the first published record of botanical exploration on Mt Munro.

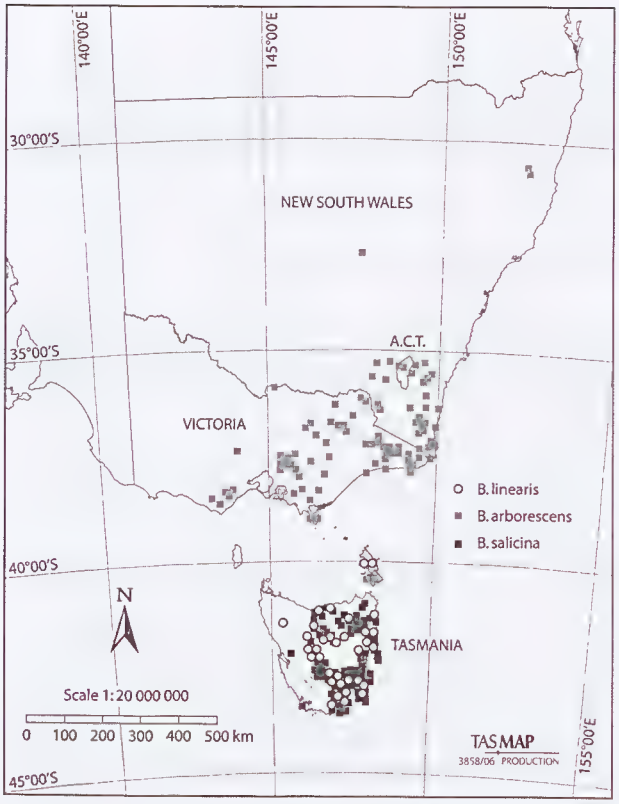

FIG. 1 — Distribution of Bedfordia *species compiled from Australian Virtual Herbarium data (March 2005).*

METHODS

This study is based on two visits to the island, in January and April 2004 during which fieldwork on foot was conducted to ground truth the vegetation map, to make notes on plots located at various sites on the mountain and to record observations on a transect across a vegetation boundary.

Description of the Study Area

Information on the geology, soils and climate was synthesised from various published and unpublished sources and field observations, to provide an environmental context for our study. This was supplemented by aerial photograph interpretation of landforms and field observations. Data collected from plots included information on environmental parameters (see population biology).

BIOCLIM modelling (Busby 1991) was used to develop a rainfall model for the Furneaux Group. BIOCLIM modelling develops a predictive surface for 27 climatic parameters encompassing temperature, precipitation and radiation variables (K. Bossard, pers. comm.) It is considered to have a high veracity for accurate rainfall predictions, and we used it to help define the environmental envelope for *B. arborescens* as well as highlight potential habitat that could be searched for the species. Some characteristics of the climate were described from field observations. BIOCLIM was run using three different sets of data combinations: Cape Barren *B. arborescens* records only; Cape Barren and/or mainland Australian records and mainland Australian records alone.

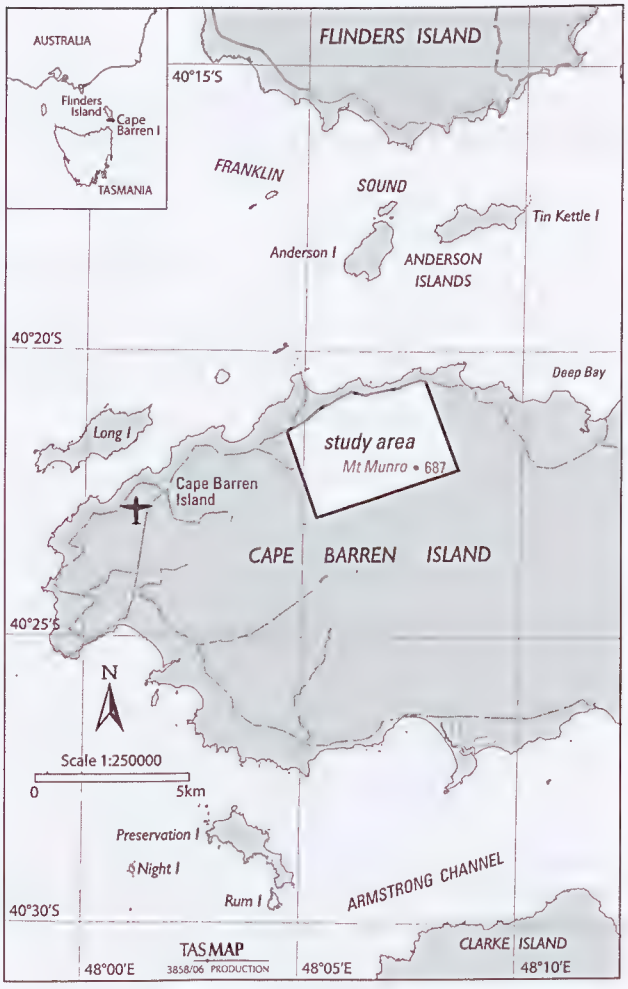

FIG. 2 — Location of study area, Cape Barren Island, Tasmania.

The Vegetation

Photo-communities were mapped from full-colour 1:42 000 scale aerial photographs dated 15 November 2003. These photo-communities were checked in the field, and where possible were allocated to TASVEG State-wide mapping communities (nomenclature follows Harris & Kitchener 2005) using species information from 33 plots of 10 m x 10 m.

One transect was laid down perpendicular to sharp grassland forest boundaries. The transect was 1100 m long and comprised 10 m x 10 m plots, spaced ten metres apart, six plots in all. Species presence and estimated absolute percentage cover values were recorded. The information from this transect was then diagrammatically illustrated. A vegetation profile was prepared to show the major changes from the coastal plain to the summit of Mt Munro. Observations along routes accessed by foot were used to supplement information from 10 m x 10 m plots located across the study area.

Historical information on the vegetation and impacts upon it were collected from published and unpublished sources. This was supplemented by an examination of earlier black and white aerial photographs dating from 14 January 1968 and 8 January 1980.

The Flora

Voucher specimens of most species observed were lodged in the Tasmanian Herbarium (HO). A search of the National Herbarium of Victoria (MEL), and the National Herbarium of New South Wales (NSW) was made for plant species collected from the island. A complete inventory of species from the mountain was not attempted.

Plant nomenclature follows Buchanan (2005) for vascular species except where authorities are given.

No systematic examination of non-vascular flora has been carried out, although some collections of lichens exist in the National Herbarium of Victoria. The cryptogamic flora is certain to be of great biogeographic interest and will repay closer scrutiny.

Population Biology and Autecology of *Bedfordia arborescens*

Location of the plots was according to the "subjective without preconceived bias" approach of Mueller-Dombois and Ellenberg (1974, p.32). Species presence, vegetation structure, soil pH measured with a CSIRO field testing kit (Inoculo Laboratories), rock type, fire history and geographical features such as aspect, altitude, topography, drainage and grid reference, were recorded for each plot. Indicators of fire history included counts of growth nodes on *Banksia marginata*, ring counts on sectioned *Leptospermum* spp., presence of fire-killed stags, downers and stems with charcoal remnants. Topographical and geomorphological features were noted from field observations and from air photo interpretation.

Girth measurements of as many specimens as time allowed were obtained with a diameter tape at breast height (1.5 m above the ground).

General observation on the habit and response of *B. arborescens* to physical damage from storms or from other limbs falling on them, and observations on historical disturbance events such as fires, were noted.

Conservation and Reservation Status

Herbarium data from the National Herbarium of Victoria (MEL) and the Tasmanian Herbarium (HO) were examined to check whether *B. arborescens* had been collected elsewhere in the region, particularly in areas that were predicted by the BIOCLIM model to be potential sites.

The authors surveyed suitable cloud forest habitat on the Strzelecki Range (Flinders Island) in September 2004.

The conservation status of *B. arborescens* was reviewed using the conservation status assessment database (Threatened Species Section, Department of Primary Industries and Water), which is based on IUCN red list categories (IUCN 1994) and modified explanatory criteria for Australian plants. The conservation and reservation status of species and communities were assessed against published lists, including the Schedules to the Tasmanian *Threatened Species Protection Act 1995*.

RESULTS

Geology, Soils and Climate

Mt Munro has numerous ridges and gullies dissecting its flanks and a plateau beneath the ultimate peak. Bedrock is prominently exposed as large slabs, tors and boulder-fields. Examples of granite-weathering phenomena such as tafoni, gnamma pits, exfoliation weathering and perched boulders occur. All of the subject area is vegetated including the apparently bare rock, which is invariably occupied by lichen-field. Some steep gullies occur as well as waterfalls, small cliffs and a small tarn. Drainage lines are incised and dendritic stream headwaters occur around the mountain. Much of the drainage from Mt Munro is to the southwest by the Modder River.

Mt Munro comprises granites similar in texture and composition to those on Wilson's Promontory and northeastern Tasmania (Burrett & Martin 1989). The soils derived from these are acid sandy loams, sometimes underlain by clay in gully sites and valley bottoms. On slopes and ridges soil is skeletal and of highly-variable depth (Pinkard & Richley 1982). In crevices, for example, soil may be more than 0.5 m deep whereas at other sites, the soil may comprise only thin accumulations of felspar and quartzite fragments.

Nowhere on the mountain, except on the floor of the deep gullies, did we observe a well-developed humic soil horizon of any note. The pH on the grassland soils was measured as 5.0–5.5 in one locality while in the forest the pH was measured as 6.0 at two sites.

Around the base of Mt Munro, there are some remnant deposits of Tertiary limestone (calcarenite) which weathers to loamy alkaline soils. In most instances the remnant calcarenite has been obscured around the base of Mt Munro by aprons of acid colluvial deposits derived from granite weathering.

Cape Barren Island is in the warm humid zone (Gentilli 1972). Although there are no meteorological stations on the island the figures for the nearest meteorological station (Bureau of Meteorology website) at Flinders Island airport 36 km to the north are used as indicative of the climate at the coast adjacent to Mt Munro. Rain falls throughout the year, with a monthly maximum of more than 219 mm in July and a minimum of 130 mm in February. The temperature is mild throughout the year with daily average temperature ranges of 13.6–22.6 °C in February and 6.2–13.3 °C in July (Bureau of Meteorology 1996). The west coast of the island, only 12 kilometres west of Mt Munro, receives the full impact of the westerly swells coming through Bass Strait.

BIOCLIM modelling indicated the rainfall on Mt Munro as 1047 mm annual average while on the coast at The Corner it is of the order of 500–600 mm annual average. There would be less evapotranspiration at the higher altitude because of the frequency of cloud capping.

B. arborescens occurs in a montane environment above 350 m altitude. Orographic precipitation from the westerly airstream is significant, and mist and cloud envelops the mountain for many days in the year, even in summer (SH unpublished data). Under certain conditions, easterly airstreams also result in dense cloud cover of the mountain. Moisture is stripped from the cloud by the vegetation.

Historical Accounts of Vegetation and Habitat

Records of vegetation character prior to the main period of human occupation in about the 1840s, are sparse, tantalising and only hint at a more extensive forest cover than exists today.

Collins (1798–1802: 152) observed from the southern side, that on Cape Barren Island: "The high part is composed of granite, in many places almost bare, in others poorly clothed with moderate sized gum trees, which draw their support through some small quantity of vegetable earth lodged by the broken blocks and fragments of the stone, and some struggling brush-wood shooting up round the trees, and completing the appearance of a continued vegetation. The base of the low part...chiefly sand, its produce, variety of brush, with some few small gum trees, and a species of fir, that grows tall and straight to the height of 20 or 25 feet".

Flinders noted in 1798 that all the islands "are over–run with brush wood; amongst which, in the more sheltered and less barren parts, are mixed a few stunted trees, which seem to shed their bark annually, and to be of the heavy kind called gum tree...". "The brush wood is commonly impenetrable..." (Flinders 1814: 132–133).

Campbell (1828: 1) reported of Cape Barren Island: "...the whole island is well wooded, the trees being the same as those generally found in Van Diemen's Land, pine trees of a small size grow here, but in no great quantities. The surface is generally covered with a thick brush, excepting on some of the barren heights where the grass tree is found...".

Backhouse & Walker (cited in Plomley 1966: 258) reported their observations from 1832: "The lofty parts of Flinders and Cape Barren are very sterile, but many of the lower hills are covered with timber of a tolerable size, chiefly blue gum. The valleys and lower grounds are, in various places, covered with tall scrub mixed with a species of *Casuarina* differing from the sheoak, and from other trees of the same genus known in the southern parts of Van Diemen's Land, but producing good small timber. The white gum is also met with. The open grassy parts of these islands are not numerous...".

Howard (1991: 85) quoted Archdeacon Reiby who observed in March 1862: "An extensive fire had been raging through and over the island, and was not quite extinguished while we went there...".

With human inhabitants on many of the large islands, the likely scenario is an increase in fire frequency (Harris & McKenny 1999, Harris *et al.* 2001). Further field evidence or historical investigation would be valuable for exploring fire history in more detail.

Many observations and reports of fires on Cape Barren Island in the past 150 years (Senior Ranger Chris Arthur, pers. comm.) indicate consequent changes in vegetation patterning and flora composition.

Description of Vegetation Communities in the Study Area

Ten vegetation communities have been mapped in the study area (figs 3, 4). The principal characteristics and species recorded in these communities are listed in table 1. Brief notes on each vegetation community are in Appendix 1.

The *Bedfordia arborescens* Community

B. arborescens occurs in rainforest with floristic similarities to the Callidendrous Sassafras-musk relict rainforest dominated by *Atherosperma moschatum* that has been described for northeastern Tasmania (Neyland & Brown 1993) (table 2).

Among co-occurring species with *B. arborescens* on Mt Munro were *Olearia argophylla, Pomaderris apetala, Pittosporum bicolor, Notelaea ligustrina* and *A. moschatum* in the canopy layer. *Dicksonia antarctica* shared the secondary layer with undershrubs including *Pimelea drupacea, Bursaria spinosa* and *Coprosma quadrifida*. The ground layer comprised scattered ferns, moss and lichen over granite boulders. Stands in which the tree occurred were generally dense with a closed canopy and often a mid-dense understorey.

The Flora

The species typical of the vegetation types were recorded (e.g., fig. 5)and have been listed above and in Appendix 1.

The flora on the mountain can be expected to have close affinities with that on the Strzelecki Mountains (Harris *et al.* 2005) 15 km north on Flinders Island and to a lesser extent with that on Blue Tier (North *et al.* 1998) in the northeast of Tasmania. *Nothofagus cunninghamii,* which occurs on Blue Tier, is lacking on Mt Munro. Mt Munro would be expected to have lower species richness than on the Strzelecki Mountains following principles of island biogeography theory. No grassland is found on the Strzelecki Mountains, and *B. arborescens* is absent.

Symptoms consistent with *Phytophthora cinnamomi* (Chromista) infection were only observed on the lower slopes of Mt Munro.

In Tasmania, the study area is floristically significant because of its combination of vegetation types. Cape Barren Island has been isolated for perhaps 8000 years and was probably devoid of human influence for at least 4000 years (Sim & Gait 1992). A combination of geographic and palaeo-environmental factors has resulted in some species and species provenances that are of conservation and scientific significance (table 3).

Population Biology of *B. arborescens*

B. arborescens is a long-lived tree producing an annual crop of abundant wind-borne short-lived seeds (pl. 1). All except the longevity are characteristics of the 'r' strategist typical of the Asteraceae. The longevity of the trees indicates a compatibility with a prolonged interval between disturbance events. The minimum interval would be the time required from germination to the first seed-set. This is not directly known from the species but by inference from the estimated fire-free intervals of communities containing *B. arborescens* is thought to be at least ten years. The plant flowers from November to January, and therefore has a short opportunity for seed distribution. If a stand was burnt, there may be no seedling regeneration from the burnt specimens. *B. arborescens* cypselas are strictly wind dispersed and regeneration would require seed from neighbouring unburnt stands. This indicates the need for a minimum population size able to withstand patch burning, and the current distribution pattern of *B. arborescens* on Mt Munro in discrete pockets would assist the

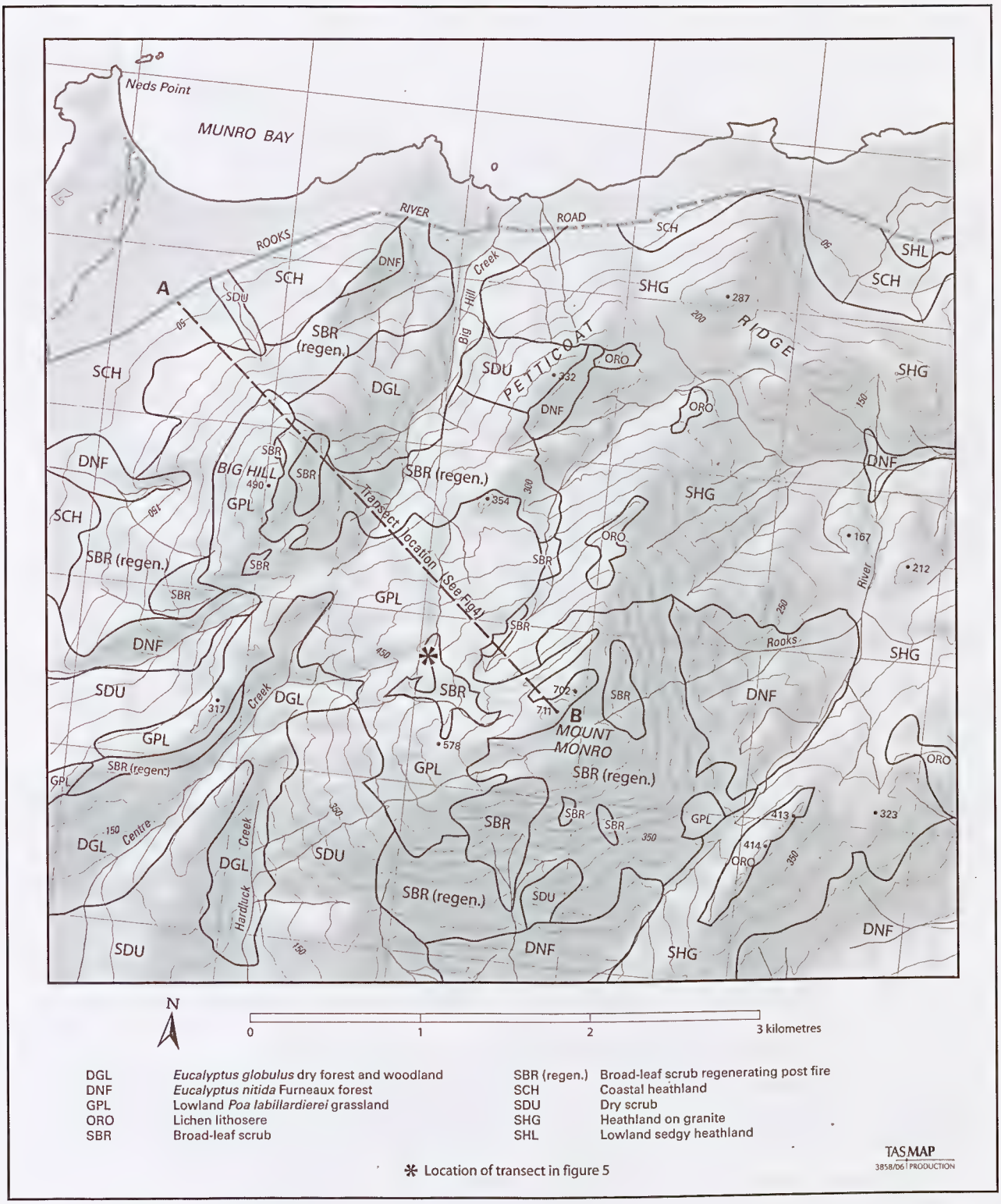

FIG. 3 — Vegetation map of study area.

perpetuation of the species. The nature of the topography on Mt Munro and the fire-protected niches in which this species occurs, prevent a single fire from destroying all the stands. The requirements of the seedlings are not known; however, presumably being highly mesophilous, some nursery crop would be required for shade. If a patch was burned, then some months may pass before seed is deposited in the site. If suitable conditions prevailed, the tree would be replaced at the site.

The relative dominance of *B. arborescens* in different forest patches of possibly varying ages may reflect the diminished cover of the species in older forests. The older forests (or rainforests) are dominated variously by combinations of *O. argophylla, A. moschatum, P. apetala, D. antarctica and B. arborescens.* In the long-term, *B. arborescens* may be a transitory species requiring fire disturbance. The grassland/forest boundary is presently the most obvious vegetation boundary on the mountain, but within the forests there

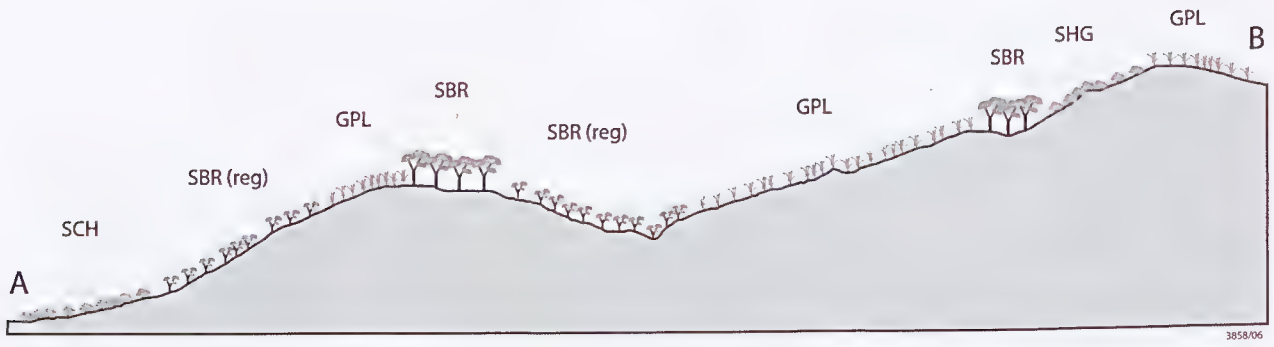

FIG. 4 — Transect diagram showing some major vegetation types in the study area.

TABLE 1
Vegetation types in the study area

Vegetation type	Dominant species	Structure (Specht 1972)	TASVEG
Rainforest and related scrub	*Atherosperma moschatum – Bedfordia arborescens – Olearia argophylla – Pomaderris apetala*	Low closed-forest	Broad-leaf scrub (SBR)
	Zieria arborescens – Gahnia grandis – Goodenia ovata – Pteridium esculentum – Lepidosperma elatius	Closed-scrub	Broad-leaf scrub (SBR) post-fire regeneration
Grassland	*Poa labillardierei – Oxalis perennans – Austrodanthonia* sp.	Closed tussock grassland	Lowland *Poa labillardierei* grassland (GPL)
Eucalypt forest and woodland	*Eucalyptus globulus – Acacia verticillata – Pimelea drupacea – Olearia lirata*	Open-forest	*E. globulus* dry forest and woodland (DGL)
	Eucalyptus nitida – Leptospermum scoparium – Kunzea ambigua	Open-forest	*E. nitida* Furneaux forest (DNF)
Heathland, scrub	*Banksia marginata – Sprengelia incarnata – Acacia* spp. *– Aotus ericoides*	Open-heath	Heathland on granite (SHG)
	Lepidosperma filiforme – Banksia marginata – Lepidosperma concavum – Baumea spp. *– Leptocarpus tenax – Hypolaena fastigiata*	Open-heath	Lowland sedgy heathland (SHL)
	Acacia spp. *– Xanthorrhoea australis – Banksia marginata – Hakea* spp.	Open-heath	Coastal heathland (SCH)
	Eucalyptus nitida – Allocasuarina monilifera – Leptospermum glaucescens – Kunzea ambigua	Open-scrub	Dry scrub (SDU)
Other natural environments	Lichens	Lichen land (in style of Specht)	Lichen lithosere (ORO)

TABLE 2
Nearest-fit vegetation classification for the *Bedfordia arborescens* forest of Mt Munro

Mt Munro cloud forest	TASVEG (Harris & Kitchener 2005)	EVC (Peel 1999)	National Land & Water Resources Audit 2001	Jarman *et al.* 1984	Neyland & Brown 1993
Bedfordia arborescens – Olearia argophylla cloud forest	Broad-leaf scrub (SBR)	Cool Temperate Rainforest	Rainforest & vine thickets (major vegetation group)	Callidendrous Sassafras-musk rainforest (C3.2)	Callidendrous Sassafras-musk rainforest

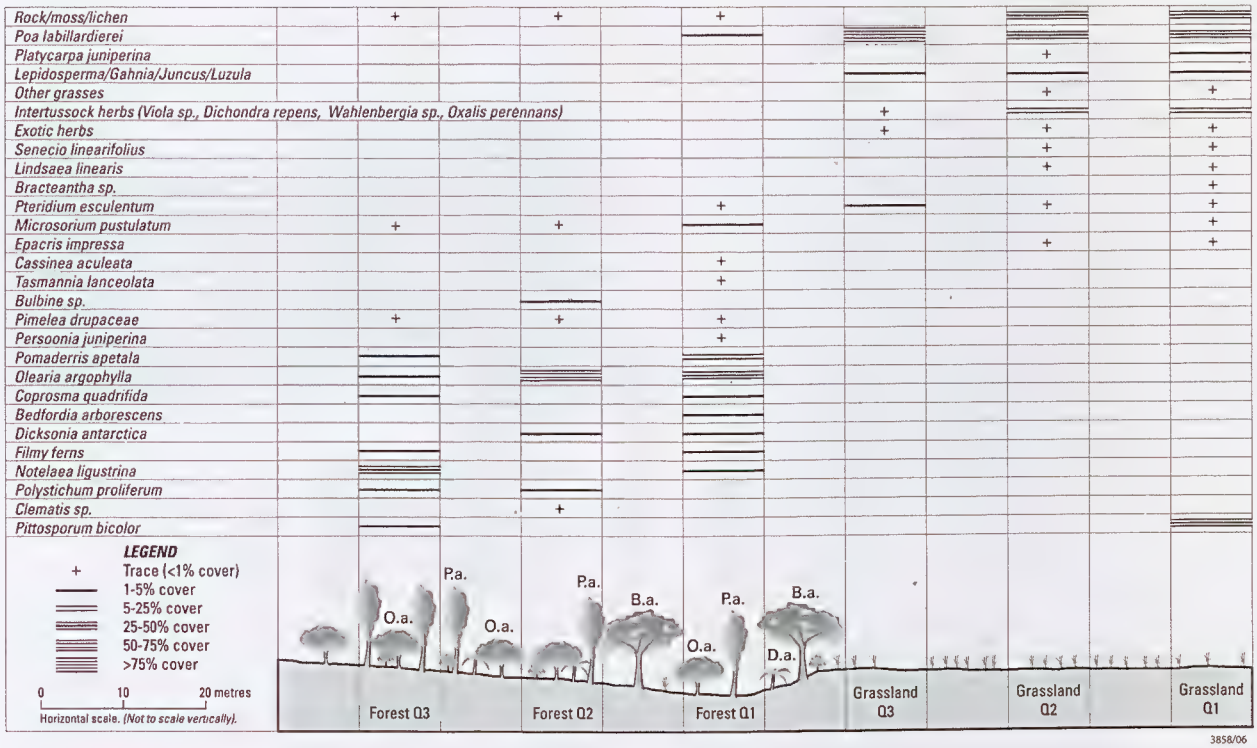

FIG. 5 — Transect diagram of floristic changes across the forest/grassland boundary.

TABLE 3
Species recorded on Mt Munro that are threatened, or are of biogeographic significance

Species	Significance
Atherosperma moschatum	Isolated population.
Bedfordia arborescens	Currently listed as rare under the Tasmanian *Threatened Species Protection Act 1995.*
Conospermum taxifolium	Not listed under the Tasmanian Act but represented by an early collection in the National Herbarium of Victoria and confirmed by Neville Walsh.
Cryptostylis leptochila	Listed as endangered under the Tasmanian *Threatened Species Protection Act 1995.* Discovered on the northeast slopes on Mt Munro, previously only known in Tasmania from Flinders Island.
Eucalyptus globulus	An internationally important silvicultural plantation species with considerable genetic variation, populations isolated on an island are of scientific significance.
Leucopogon esquamatus	Listed as rare under the Tasmanian *Threatened Species Protection Act 1995.* Occurs extensively in the heathland below the slopes of Mt Munro.
Lomatia tinctoria	Endemic in Tasmania, close to northern extent of distribution.
Pseudanthus ovalifolius	Uncommon in Tasmania, confined to gravelly, siliceous soils in eastern parts of the State and the three largest islands in the Furneaux Group.
Spyridium gunnii	Isolated population, in the Furneaux Group found only on higher peaks.

PLATE 1
The seed of Bedfordia arborescens.

are boundaries between patches of varying dominance reflecting different fire ages. The patches of *B. arborescens*-dominated forest, if remaining unburnt, will be reinvaded by *A. moschatum, D. antarctica* and other rainforest species. *B. arborescens* may represent a successional stage within the forest.

Tree diameter is known to be a poor proxy for age because tree diameter increments are known to respond strongly to site conditions. If, however, diameters are aggregated into size classes, then some general inferences can be drawn. First, no small trees with diameters less than 5.8 cm were found, indicating an absence of recruitment below the ages this size may represent. Most trees that were measured fall in diameter class ranges between 5 and 25 cm. Fewer specimens then occurred up to 39 cm. A large gap exists up to the largest individual measured at 55 cm dbh (fig. 6). This specimen may represent a small number of trees on the mountain that have survived from a much earlier cohort than is represented by other measured trees. This would indicate a recruitment gap with missing cohorts that could mean that disturbance across the mountain retarded recruitment of *B. arborescens* for some period of time. It is possible that the largest individual represents a surviving cohort from pre-settlement disturbance and the size gap below this indicates the beginning of new stands resulting from a period of high fire frequency.

PLATE 2
Bedfordia arborescens *killed by fire on Mt Munro.*

Autecology

B. arborescens occurs as a robust, umbrageous tree 6–8 m high in the study area. Observation of individuals showed that they were always in a healthy condition with no senescence. Where physical damage had occurred to individual trees, such as breakage from wind throw, there was an epicormic response on broken limbs, provided there was still bark continuity. Shoots thus produced have a strong apical dominance, taking advantage of a break in the canopy cover. These fast-growing shoots contrast with the spreading foliage of dominant *Bedfordia* trees in the forest that have probably regenerated in a single cohort and subsequently self-thinned. In the apparently older forests, some physical damage of individuals was observed. It is not clear whether this had resulted from direct or indirect wind throw damage, or whether the trees are nearing the end of their life span.

The species is killed by fire. This is apparent through examining the pattern of vegetation boundaries. Instances were observed where dead *B. arborescens* occurred behind a fire boundary (pl. 2). The adaptive significance of the thick, spongy bark in mature specimens is uncertain in this context. We did note, however, during heavy mist, that water was being captured by the crown and directed down the bark fissures. This might be an adaptive mechanism for a cloud-stripping species. The foliage is mesophilous and rapidly wilts if conditions become dry. The species may therefore be intolerant of prolonged dry conditions. Epicormic recovery is likely to occur, following fire as it is a common response in *Bedfordia salicina.*

Reservation and Conservation Status of *B. arborescens*

B. arborescens is not known to occur within any reserve in Tasmania and its total extent is on Aboriginal land. The BIOCLIM predictions suggested that suitable climatic habitat existed in northeastern Tasmania in the Blue Tier and mounts Victoria and Albert region. Interestingly, no suitable climatic habitat was predicted anywhere else in the Furneaux Islands beyond Mt Munro. This is despite the existence on Flinders Island of mountains with cloud forest and many other shared species (Harris *et al.* unpubl. data). One prediction gave a high probability of *B. arborescens* occurring to the east of our own field records. We believe this is possible, as the area is

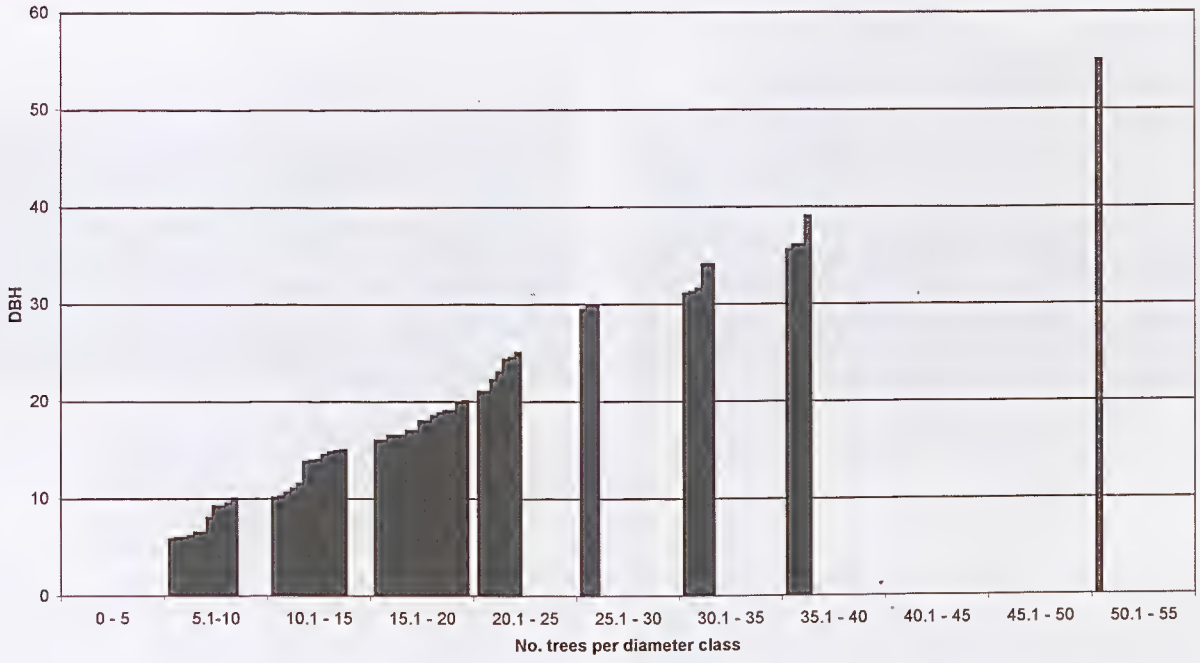

FIG. 6 — Diameter classes of Bedfordia arborescens *on Mt Munro.*

still on the Mt Munro massif and the compatible vegetation occurs in the predicted region. Confirmation must await further visits. Targeted surveys in likely habitat on Flinders Island to the north failed to locate the species.

Presently, *B. arborescens* is listed as rare on schedule 5 of the Tasmanian *Threatened Species Protection Act 1995* and was designated an R1 species (Flora Advisory Committee 1994). No *Bedfordia* is listed as threatened in other States.

Given current data, *B. arborescens* qualifies for listing as vulnerable at the State level using the guidelines for the listing of species on the Tasmanian *Threatened Species Protection Act 1995* because:

- there are fewer than 10,000 mature individuals;
- there is no population with over 1,000 individuals;
- there is a continuing decline. A continuing decline is inferred due to a high fire frequency on the island.

GENERAL DISCUSSION AND MANANGEMENT RECOMMENDATIONS

This study represents the first examination of the habitat, ecology and status of *B. arborescens* in Tasmania and must be viewed as a reconnaissance-level examination. Our discussion is limited by the lack of studies on the genus elsewhere.

Our observations are consistent with the general ecology of members of the Asteraceae, many of which regenerate prolifically, especially after disturbance. In this case, however, these attributes are applied in the context of a long-lived tree in an unusual environment, which is significant. Tree-form Asteraceae are uncommon worldwide. Notable examples of gigantism in herbaceous Asteraceae are reported in situations that are either islands or habitat islands on mountains in a continental situation. Examples are described in the literature from Africa, and on a number of oceanic islands. These include *Senecio huntii* from the Chatham Islands and *S. stewartiae* from the islands in the Foveaux Strait in New Zealand (Allen 1982).

Bedfordia is not common in the Furneaux Islands. A search of collections in the Tasmanian Herbarium reveals no records of *B. salicina* from the Furneaux Islands. *B. linearis* has been recorded from Flinders Island at Broughams Sugarloaf, Summer Camp Gully and near Emita. The taxonomic boundary between *B. salicina* and *B. linearis* has been regarded as indistinct by some fieldworkers (Kirkpatrick & Backhouse 2004). We believe *B. arborescens* on Cape Barren Island to be very distinctive from forms of *B. salicina* or *B. linearis*. It is likely that the genetic make up of this population varies significantly from mainland populations. This would result from separation of populations over a span of at least 10,000 years (being the time since the post-glacial formation of Bass Strait).

The long-term survival of *B. arborescens* here must be considered in the context of the vegetation pattern on the mountain and the natural and human processes shaping it. Over successive glacial cycles Mt Munro has, alternately, been a high point on an extensive plain (Jackson 1990) between the mountains of Wilsons Promontory and northeast Tasmania, and an island mountain surrounded by seas. Apart from Cape Barren Island and the other major islands in the Furneaux Group, there is nowhere else in Australia where we can confidently say that humans were absent for a period of approximately 4500 years during the Holocene. Since human occupation and visits to Cape Barren Island recommenced about 200 years ago, fire frequency is likely to have increased. The interactions of fire and biophysical variables have created an interesting vegetation pattern.

The vegetation map indicates a zone of cloud forest, generally above 280–300 m altitude, below which heathland, scrub and eucalypt forests occur. This transition may have been differently expressed in the vegetation 200 years ago. Repeated firing has reduced the general stature of vegetation and eroded the distribution of tall forests and fire-prone forests to the extent that these now occur only in more fire-protected sites on the mountain. Open heathland and scrub may have replaced forests and woodlands of *Eucalyptus nitida*,

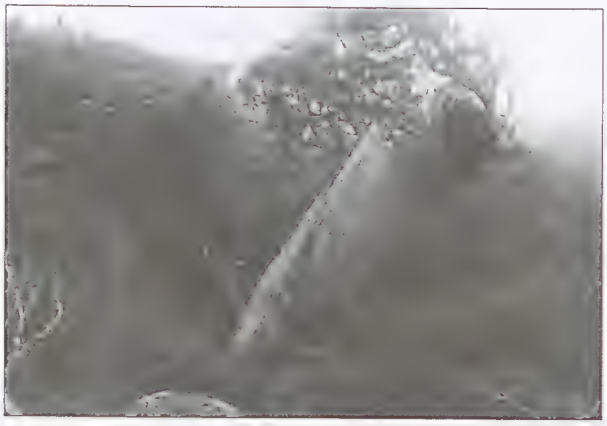

PLATE 3
Eucalyptus *(probably* globulus*) stag on the edge of* Bedfordia arborescens *cloud forest*

PLATE 4
Eucalyptus *(probably* globulus*) stags scattered over grassland adjacent to relict* Bedfordia arborescens *stand.*

as well as *Callitris rhomboidea* with dense understorey of *X. australis*. Remnant bluegum forest with open understorey and with bracken as a prominent ground species may have replaced tall *E. globulus* forests with dense understorey. Vegetative reproducers and anemophilous species appear to exceed the biomass of the few obligate seeders. Above the base of the cloud layer, forest once dominated by *A. moschatum* has been replaced by forest dominated by *P. apetala, B. arborescens, Acacia verticillata* and *N. ligustrina*. These forests in turn have been replaced by scrub dominated by *Leptospermum* sp., *A. verticillata, Zieria arborescens* and *Lepidosperma elatius*.

The interception of water from the atmosphere results in cloud forest and has been widely documented in tropical and subtropical systems (Hutley *et al.* 1997, Bruijnzeel & Veneklaas 1998).

Emergent trees with large leaf surface areas may account for increased annual precipitation totals of the order of 200% through the action of "cloud drip" (Page 1979 cited in Rigg *et al.* 2002). Dense populations of epiphytic cryptogams and ferns often typify such forests. The *B. arborescens* on Mt Munro appear to have abundant epiphytic cryptogams and ferns.

The disclimax grasslands on the mountain are comparable with the subalpine grasslands in northeast Tasmania (Ellis 1985, Ellis & Grayley 1987) where the destruction of rainforest by fire has resulted in the creation of grasslands. The remains of *Eucalyptus* (probably *globulus*) stags and downers on Mt Munro indicate the previous vegetation type (pls 3, 4). On Flinders Island, *Poa* grasslands resulting from repeated firing of eucalypt forest have developed on Walker's Lookout in the Darling Range.

The grassy ridgetops of the Mt Munro massif may be analogous with the montane grasslands within the matrix of rainforest that occurs in parts of New Guinea. Paijmans (1976) states that fires on Mt Wilhelm are more irregular than in lowland grassland because of the greater dampness, the shorter and less reliable dry season and the more abundant wet and less flammable patches. The effect of fires in this environment produces a mosaic of successional and subclimax stages. He also points out that certain grasses prefer crests in New Guinea where fire is more frequent.

Anthropogenic firing is a likely cause of grassy balds or grasslands in grassland/forest mosaics. Fensham & Fairfax (1996) describe such a mosaic in the Bunya Mountains in Queensland where no strong environmental correlation is apparent with the occurrence of grassland, and disturbance such as firing is the most likely explanation.

Fire management on Cape Barren Island, until as recently as about five years ago, involved frequent burning carried out by the island inhabitants. A Parks and Wildlife Service ranger stated that "The island was burnt in large patches traditionally every 3 to 4 years" (C. Arthur, letter to N. Walsh 2004). Prior to human settlement in the Bass Strait islands, it seems likely, by inference from the historical records available to us, that there was extensive forest and scrub vegetation on Cape Barren Island. There are insufficient historical observations for confidently reconstructing in any detail the pre-settlement vegetation. However, the present patterns are consistent with a high fire frequency over at least the past hundred years.

On Mt Munro the extent of cloud forest dominated by *A. moschatum* and *B. arborescens* and other trees, appears to have been eroded by fire in historical times. The grassland has been maintained by frequent low-intensity fires that have also allowed preservation of remnant cloud forest through reinforcement of sharp differences in soil moisture and nature of fuels. The prevalence of large downers of what are likely to be *E. globulus*, suggests that prior to the pyrogenesis of the grasslands, the previous fire would have dated from the origin of the eucalypts now lying on the grassland floor. The eucalypts probably represented scattered emergents over a rainforest understorey, probably acting as a "nursery tree" harvesting moisture from clouds and increasing the moisture availability to the immediate understorey, in the same way as indicated for *Araucaria laubenfelsii* on Mt Do in New Caledonia (Rigg *et al.* 2002). An alternative hypothesis is that the eucalypt litter allowed the fire to penetrate where they were present and that the stands without eucalypts were relatively fire resistant.

The Broad-leaf scrub (SBR) community has the potential to reach a rainforest climax provided there are suitable seed sources in the vicinity.

There are possibly strong affinities with some of the rainforest communities described by Peel (1999) for Victoria. These include warm temperate rainforest and dry rainforest communities such as the "East Gippsland overlap warm temperate rainforest" community and the "coastal range overlap warm temperate rainforest" community. The floristic similarities of the Mt Munro stands and some of

PLATE 5
The sharp forest/grassland boundary on the upper slopes of Mt Munro.

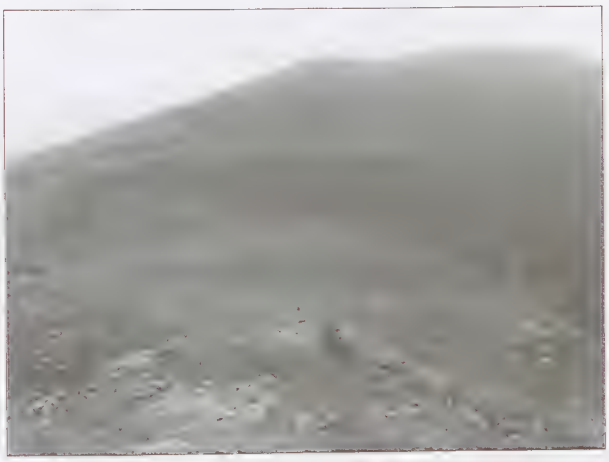

PLATE 6
Fire induced and maintained vegetation patterning above the lower limit of the cloud cap on Mt Munro.

the quadrats in the Victorian study are very strong. *B. arborescens* on Cape Barren Island occurs within (or close to) the Tasmanian range of several rainforest outliers that comprise the companions to *B. arborescens* in Victoria. These include *Elaeocarpus reticulatus*, *Pandorea pandorana* (on nearby Flinders Island), *Polyscias* spp. and *Pomaderris aspera*. The environmentally-limiting factors for *B. arborescens* will not be identified until experimental work is carried out on the species. This will be difficult, as there has been almost no success reported for seed germination from Mt Munro collections (W. Fletcher, Plants of Tasmania Nursery, pers. comm.) although in Victoria, Dr David Ashton (University of Melbourne, pers. comm.) germinated seedlings from handfuls of sieved soil incubated in a glasshouse for some months.

The reservation and conservation status of the *B. arborescens* deserves attention. The former Crown land on Cape Barren Island was vested in the Aboriginal community in March 2005. The International Union for the Conservation of Nature has specified a classification of reserves. Category V Protected Landscape states as one of its primary management objectives, "to provide for use by either Aboriginal or non-Aboriginal communities for those traditional activities that are important in determining the distinct ecological characteristics of the area". Such a category would be compatible with Mt Munro on Cape Barren Island. Alternatively a discrete area of highly significant nature conservation values could be formally designated as a Strict Nature Reserve (Category 1a under IUCN). The conservation status of *B. arborescens* has been reassessed as vulnerable, and this paper will be useful to inform the process of uplisting the species.

Peripheral populations of species are known to be valuable for conservation because there is likely to have been genetic divergence from central populations. Advantages of conserving such peripheral populations have been described by Lessica & Allendorf (1995). A study of the genetic make-up across the total range of *B. arborescens* would be of fundamental interest, as it would establish whether the Cape Barren Island population was a genotype distinct from the mainland. If so, its conservation importance may be considered to be greater. The genetic variation between forest pockets on Mt Munro would be of interest also. We hypothesise that there would be no significant differences across these sub-populations, but also that there may well be differences between Cape Barren Island and mainland Australian populations. The 10,000 years since the beginning of the Holocene is enough time to produce genetic drift. Genetic studies would therefore be valuable for understanding the species. The importance of such work as a background for species conservation planning is demonstrated by Shapcott (1994), who investigated a rainforest species that may have some parallels with *B. arborescens*. There is scope for research on a variety of topics that would broaden our understanding of this species and its ecology, as well as assist its management in the long term.

Our work has indicated that this species is strictly an 'r' strategist, but is likely to rely on a narrow temporal opportunity for establishment following fire. No evidence of gap phase or continuous regeneration is apparent; however, it appears that a major disturbance event such as fire will encourage establishment. The grassland areas between stands of rainforest with *B. arborescens* are likely to be hostile to seedling regeneration because of water stress, grass competition and high insolation, particularly in the absence of any nursery crop. Regeneration of *Bedfordia*, on the other hand, may be optimal where forest patches are burned in the occasional intense fire. That is, the relict rainforest patches that currently occupy gullies or shaded slopes and containing *B. arborescens* may need occasional fire for regeneration of *B. arborescens*. Propagules from adjacent patches would be blown into these areas, and may have a higher likelihood of establishment due to the naturally damper substrate and the probability of a rapidly regenerating nursery crop, for example of *Z. arborescens*. Under the current regime of frequent fires, the grassland/forest boundary (pl. 5) is being reinforced and fire incursion into the forest is most likely rare because of the limited fire carrying capacity of the adjacent grassland.

Studies elsewhere (e.g., Duncan & Duncan 2000) indicate that forest succession into grasslands can be very slow, partly because of competition for nutrients and the especially vigorous nature of grasses. Fensham & Kirkpatrick (1992)

have demonstrated in the Tasmanian Highlands that the development of a dense grass sward is inhibitive to the establishment of trees.

Further research on *B. arborescens* is required before it is possible to be confident about species and habitat management directions.

The existing vegetation pattern (pl. 6) is likely to reflect a higher fire frequency over the past 200 years than previously. There is currently no fire management plan for Cape Barren Island. Discussion between natural resource managers and local Aboriginal land managers would assist the development of an ecologically sustainable fire frequency.

Evidence of vehicle tracks was observed on Big Hill and adjacent flanking ridges. Easy access by vehicle can facilitate damaging activities to occur. The tracks appeared to be relatively recent in March 2004; however, with the increase in capability and versatility of off-road vehicles, motorised access could penetrate many more parts of the mountain, to the detriment of natural values. Such activities could be controlled through specifications in a formal management plan and its subsequent enforcement.

Managers of threatened species need to consider the long-term impacts of global and regional climate change. Loss of climatic habitat caused by anthropogenic emissions of greenhouse gases is listed as a key threatening process under the provisions of section 183 of the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999*. The trends indicate that global warming is occurring, particularly an increase in minimum temperatures (CSIRO 2004). Projections for seasonal and annual warming ranges indicate increases up to around 4° C by 2070. A recent study predicted a modest increase in temperature of less than 1° C by 2040, and northeastern Tasmania becoming drier by 70–140 mm (McIntosh *et al.* 2005). A general decrease in summer rainfall and an increase in winter rainfall in Tasmania is predicted. It is not possible to be very accurate about the changes for this locality, although it is likely that there will continue to be climatic conditions conducive to maintenance of the existing vegetation pattern in the next 40 years at least. While studies have been made on possible climatic-induced changes to tropical cloud forests (Loope & Giambelluca 1998, Foster 2001) the future of extra-tropical cloud forests is uncertain. Long-term monitoring of vegetation and selected climatic variables on Mt Munro would be of great interest for understanding the long-term outlook here for *B. arborescens*.

Specific changes to the microclimate of Mt Munro may already have been occurring over the past 200 years as a result of a very high fire frequency on the surrounding plains that has converted forest and woodland to heath and sedgeland. Evidence for tropical montane cloud forests (Lawton *et al.* 2001) indicates ascension of the cloud base following clearing of surrounding lowland forest. We are uncertain about the applicability of this tropical situation to the Mt Munro environment, where montane forest was formerly surrounded by dry forest rather than rainforest.

Ex-situ conservation strategies, particularly given that the seed may be classed as recalcitrant, may be limited. Long-term storage of the seed in a seed bank may therefore not be an option; however, viability and longevity of seed should be assessed. Before *ex-situ* measures are considered, a fire management plan for the mountain and surrounding areas suggests itself as a priority. Continued liaison between the community Cape Barren Island Aboriginal Association and vegetation ecologists would be productive in considering fire management of the unique vegetation of Mt Munro.

The remnants of the cloud forest represent habitats that are unusual, or at least rarely recorded, in the scientific literature for temperate and Mediterranean climates. The presence of cloud stripping forest is the likely reason for the persistence on Mt Munro of the outlying population of *B. arborescens*, remote from its nearest neighbours on mainland Australia.

ACKNOWLEDGEMENTS

We are indebted to the Cape Barren Island Aboriginal Association, particularly Sue Summers, Vicki Little and Daryl Padman for encouragement and logistical support and Spencer Chung for drawing the figures. Karl Bossard at the Environmental Resources Information Network in the Australian Department of Environment and Heritage was very helpful in running the BIOCLIM predictions. We are grateful to the late Dr David Ashton of the University of Melbourne for his invaluable comments on a draft of this paper.

Natalie Papworth from the Royal Tasmanian Botanical Gardens assessed and photographed the *B. arborescens* seed. We thank Alex Buchanan, the late Dr Dennis Morris and colleagues at the Tasmanian Herbarium for confirming some of our species identifications. Catherine Gallagher of the National Herbarium of Victoria assisted with information about material in their collection. Phil Cullen is thanked for his provision of nine plot descriptions. Kathryn Jerie ably assisted in the field during one of the site visits. Our referees provided useful comments on a draft of the paper.

We dedicate this paper to the memory of Dr Irynej Skira (1950–2005) who made a substantial contribution to knowledge of the wildlife and history of the Furneaux Islands.

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(accepted 2 October 2006)

APPENDIX 1

Short descriptions of vegetation communities in the study area. Nomenclature follows Harris & Kitchener (2005).

Broad-leaf scrub (SBR)

This short rainforest is generally up to 8–10 m high with a dense canopy and open understorey in most cases. It occurs in gullies, depressions and shaded slopes but has abrupt boundaries with some other communities. *Eucalyptus globulus* may have been a more common emergent in these forests. Fire frequency is very low.

Species observed in this community include *B. arborescens, A. moschatum, Olearia argophylla, P. apetala, N. ligustrina, Acacia melanoxylon, Leptecophylla juniperina, P. drupacea, P. bicolor, C. quadrifida, Z. arborescens, Senecio* sp., *Cyathea australis, Asplenium bulbiferum, Pellaea falcata, Polystichum proliferum, Histiopteris incisa, Hypolepis* sp., *Hymenophyllum australe, Hymenophyllum cupressoides, Hymenophyllum flabellatum, Parsonsia straminea, Ctenopteris heterophylla, Rumohra adiantiformis, Polyphlebium venosum, Clematis aristata, D. antarctica* and *Microsorum pustulatum.*

Broad-leaf scrub (SBR) post-fire regeneration

This community is extensive around the mountain and generally occurs above the lower limit of the cloud forest effect. It comprises dense *Z. arborescens* associated with some other species. There are often large *Eucalyptus* downers.

Species observed in this community include *Z. arborescens, L. elatius, Gahnia grandis, Goodenia ovata, A. verticillata, Olearia lirata, Pteridium esculentum, E. globulus* (occasional emergent), *E. nitida* (occasional emergent), *P. drupacea* and *M. pustulatum.*

Lowland Poa labillardierei grassland (GPL)

This grassland occurs on the higher ridges and slopes below Mt Munro and often has sharp boundaries with other communities. It is an apparent fire disclimax community because there are numerous logs on the ground from burnt *E. globulus* emergents over rainforest. The grassland is dominated by *P. labillardierei* with a number of herbs, shrubs and other grasses.

Species observed in the community include *P. labillardierei, Kunzea ambigua, Allocasuarina verticillata, Aira* sp., *Austrodanthonia* sp., *Trifolium* sp., *Asteraceae* sp., *Oxalis perennans, Hydrocotyle* sp. *Ehrharta* sp., *Asperula* sp., *P. esculentum, L. juniperina, Epacris impressa, Juncus* sp., *Lepidosperma* sp., *Gahnia* sp., *Lindsaea linearis, Austrodanthonia* sp. *Luzula* sp., *Viola* sp., *Acetosella vulgaris, Dichondra repens.* and *Wahlenbergia* sp.

Eucalyptus globulus dry forest and woodland (DGL)

E. globulus forest and woodland was probably more extensive around Mt Munro but the dominant tree has been killed by fire. It is commonly a tall forest up to 25 m high with prolific shrub layer that includes many of the mesophilous shrubs listed under broad-leaf scrub. Above the lower limit of the cloud cap, *E. globulus* has the potential to persist over rainforest understorey.

Species observed in the community include most of those listed under broad-leaf scrub and broad-leaf scrub (post-fire regeneration).

Eucalyptus nitida Furneaux forest (DNF)

One of the most common eucalypt forest types in the Furneaux Islands, this community ranges from short forest and woodland to tall forest. In the study area, the community occurs as young forest 8–10 m high to older forest up to 20 m high. This forest is more typical of very low nutrient soils and drier sites than *E. globulus* forest. The two eucalypts are occasionally found together. Often there is a dense shrub layer in gullies and higher slopes.

Species observed in the community include, at the wetter end of the spectrum, many of the species found in *E. globulus* forest. In the drier forest at lower altitudes in the study area, the following species were observed: *Leptospermum scoparium, K. ambigua, Lasiopetalum macrophyllum, G. grandis, Xanthorrhoea australis, Acacia mucronata, O. lirata, Correa reflexa* and *L. elatius.*

Heathland on granite (SHG)

This is an extensive heathland type in the study area. Although the heathland is capable of succeeding to scrub and forest, frequent fires have maintained the heathland formation. Mallee form *E. nitida* is commonly scattered throughout and the understorey is characterised by a diverse shrubby flora or a graminoid-dominated flora where *P. cinnamomi* has affected the community in which case it is mapped as Lowland sedgy heathland.

Species observed in this community include *Acacia genistifolia, A. mucronata, P. apetala, Callistemon viridiflorus, C. quadrifida, Leptomeria drupacea, K. ambigua, Lepidosperma concavum, Acacia myrtifolia, Hakea epiglottis, Persoonia juniperina, X. australis, Hakea nodosa, Hakea teretifolia, B. marginata, Leptospermum glaucescens, Allocasuarina monilifera, L.scoparium* and *Cryptostylis leptochila.*

Lowland sedgy heathland (SHL)

This heathland community is an artefact of extensive *P. cinnamomi* infection, which has eliminated many plants from susceptible families. The result is a graminoid-dominated heathland on slopes with fairly uniform drainage. The species composition is a depauperate version of the coastal heathland community. The dominant graminoids in this community type include *Lepidosperma filiforme, L. concavum, Baumea* spp., *Leptocarpus tenax* and *Hypolaena fastigiata.*

Coastal heathland (SCH)

This community occurs in the lowest altitude sites in the study area on coastal sand and other siliceous sediments where *P. cinnamomi* has had a minimal effect and shrub diversity is high.

Species observed in this community include *A. genistifolia, L. glaucescens, Xanthosia pilosa, Leucopogon collinus, L. concavum, H. fastigiata, A. myrtifolia, X. australis, Dillwynia* sp., *Acacia suaveolens, B. marginata, E. impressa, Patersonia fragilis, Selaginella uliginosa, Dampiera stricta, H. teretifolia, P. juniperina, Aotus ericoides, Lomatia tinctoria, Pseudanthus ovalifolius, Platylobium triangulare* and *Leucopogon esquamatus.*

Dry scrub (SDU)

This community is common throughout the Furneaux Group especially on Cape Barren Island, where frequent fires have given expression to an abundance of early successional stages. Species such as *L. scoparium, A. mucronata, A. verticillata* and *B. marginata* have the potential to become trees. Due to the density of the scrub there is usually low species diversity but some species may be entirely represented by soil stored seed that would germinate after fire.

Species observed in this community include the longer-lived elements from coastal and lowland sedgy heathland.

Lichen lithosere (ORO)

This community occurs on extensive areas where the granite bedrock is at the surface. Shrubs and vascular plants may occur in crevices but the dominant flora are cryptogams.

THE TAMAR TROUGH REVISITED: CORRELATIONS BETWEEN SEDIMENTARY BEDS, BASALTS, THEIR AGES AND VALLEY EVOLUTION, NORTH TASMANIA

by F.L. Sutherland, I.T. Graham, S.M. Forsyth, H. Zwingmann and J.L. Everard

(with eight text-figures, two plates, nine tables and two appendices)

Sutherland, F.L., Graham, I.T., Forsyth, S.M., Zwingmann, H. & Everard, J.L. 2006 (30:xi). The Tamar Trough revisited: correlations between sedimentary beds, basalts, their ages and valley evolution, North Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 140: 49–72. ISSN 0080–4703. Geoscience, Australian Museum, 6 College Street, Sydney, New South Wales 2010, Australia (FLS*, ITG); Tasmanian Geological Survey, Mineral Resources Tasmania, PO Box 56, Rosny Park, Tasmania 7018, Australia (SMF, JLE); CSIRO Division of Petroleum Resources & Centre of Excellence in Mass Spectrometry, School of Applied Geology, Curtin University, Western Australia 6102, Australia (HZ). *Author for correspondence.

The Tamar Trough, an Early Palaeogene fault structure, contains sedimentary beds and interleaved basaltic flows that infill the structure along its 70 km length. These infills represent a complex interplay between sedimentation, channel erosion, eruptive dislocations, and even 'out of trough' diversions of the ancestral Tamar drainage. Several areas of resistant basalt flows remain in the south, upper, middle and lower Tamar reaches. Although some palynological control was known, radiometric dating of previously untested basalts now allows close integration and age-pegging for observed palynological biozones. The K-Ar and Ar-Ar ages of the basalt bodies indicate eruptive events at 47, 33–37 and 25 Ma, correlating with *Proteacidites asperopolus-Malvacipollis diversus*, *Nothofagites asperus* and *Proteacidites tuberculatus* biozone age sedimentary beds respectively. Basanite, alkali basalt and hawaiite flows dominate basalt lithology with lesser olivine nephelinite, transitional olivine basalt, olivine tholeiite and quartz tholeiite. Basalt geochemistry suggests derivation from different degrees of partial mantle melting (from 7 to 35%), with alkaline and tholeiitic basalts being derived from separate source regions. Most alkaline basalts have high-μ (HIMU) related trace element signatures, which are absent in the tholeiitic rocks. A basalt plug on the trough margin at Loira gave a Jurassic age and has Jurassic dolerite-like geochemistry. The Tamar sequence suggests that the initial fluvio-lacustrine and later channel-fill sedimentation from 65(?) to 24(?) Ma was then punctuated in places by periods of alkaline volcanism between 47 to 33(?) Ma, and alkaline and tholeiitic volcanism between 33 to 24(?) Ma. No Neogene fossils are known, so this later period was probably one of net erosion. These contrasting quiet sedimentary and more volcanic intervals are related here to a tectonic model that involves northerly drift of Victorian and Tasmanian lithosphere over several former Tasman metasomatised mantle plume sources.

Key Words: Tamar Trough, Cenozoic, palynostratigraphy, basalt dating, volcanism.

INTRODUCTION

Half grabens and grabens form the Tamar Trough, an in-filled structure developed by latest Cretaceous to earliest Cenozoic rifting (Forsyth 1989) that was linked to faulting that formed the Bass Basin (Morrison & Davidson 1989). This 70-km long, NNW trending fault structure is an offshoot of the Longford sub-basin fault structure (Matthews 1989, Direen & Leaman 1997). Basalt flows are exposed or encountered in cores drilled within the Trough sequence and these have diverted old river courses, particularly in the south where the South Esk was finally deflected west to enter the Tamar River at Launceston (Carey 1946, Sutherland 1971). The basalt samples were studied in petrographic detail and some contain mantle and/or lower crustal xenoliths and xenocrysts (Sutherland 1969, 1971, Everard 1990, 2001, Sutherland *et al.* 2004, and this paper).

Apart from the relationships of the basalt flows to the sedimentary beds, which have some palynological control, the lack of precise radiometric dating on the basalt flows has hampered integration of the sedimentary deposition, volcanism and geomorphic evolution within the trough. An improved understanding of the trough geology has importance, as the interfaces of soft sedimentary beds and resistant basalt flows promote slope movements and hence create problems within housing and construction developments (Turner 1975, Mazengarb 2004).

Extensive palaeobotanical studies exist on Cenozoic sedimentary sequences, including papers of international significance (Hill 1987). Most of the palaeostratigraphic dates, however, are based on biostratigraphy from offshore cores in Bass Strait, from sites over 100 km away and from very different depositional environments. The present work aims for more direct dating of the local Tamar biostratigraphy.

This paper documents new radiometric dating and petrological data on the basalts along the length of the Tamar Trough. Seven basalts were dated by K-Ar methods, with follow up Ar-Ar dating on three basalts. New analyses of the basalts are presented, as the earlier published petrology lacked trace element data and some further basalt sites were located by later mapping and drilling within the Tamar Trough. This present study is used to correlate the eruptive basaltic episodes with the known palynological zones within the Tamar sediments and thus refine the stratigraphy. The integrated dating will help to establish the drainage evolution that produced the present Tamar River system. Finally, the updated Tamar Trough evolution will be evaluated within the known overall tectonic setting of Tasmania and its Cenozoic volcanism.

GEOLOGICAL SETTING

The geology of the general area (fig. 1) lies within the Northeast Tasmania 1:250 000 Geological Sheet (McClenaghan *et al.* 2005), which utilises earlier mapping. The study area from north to south is covered by the 1:63 360 Geological Maps

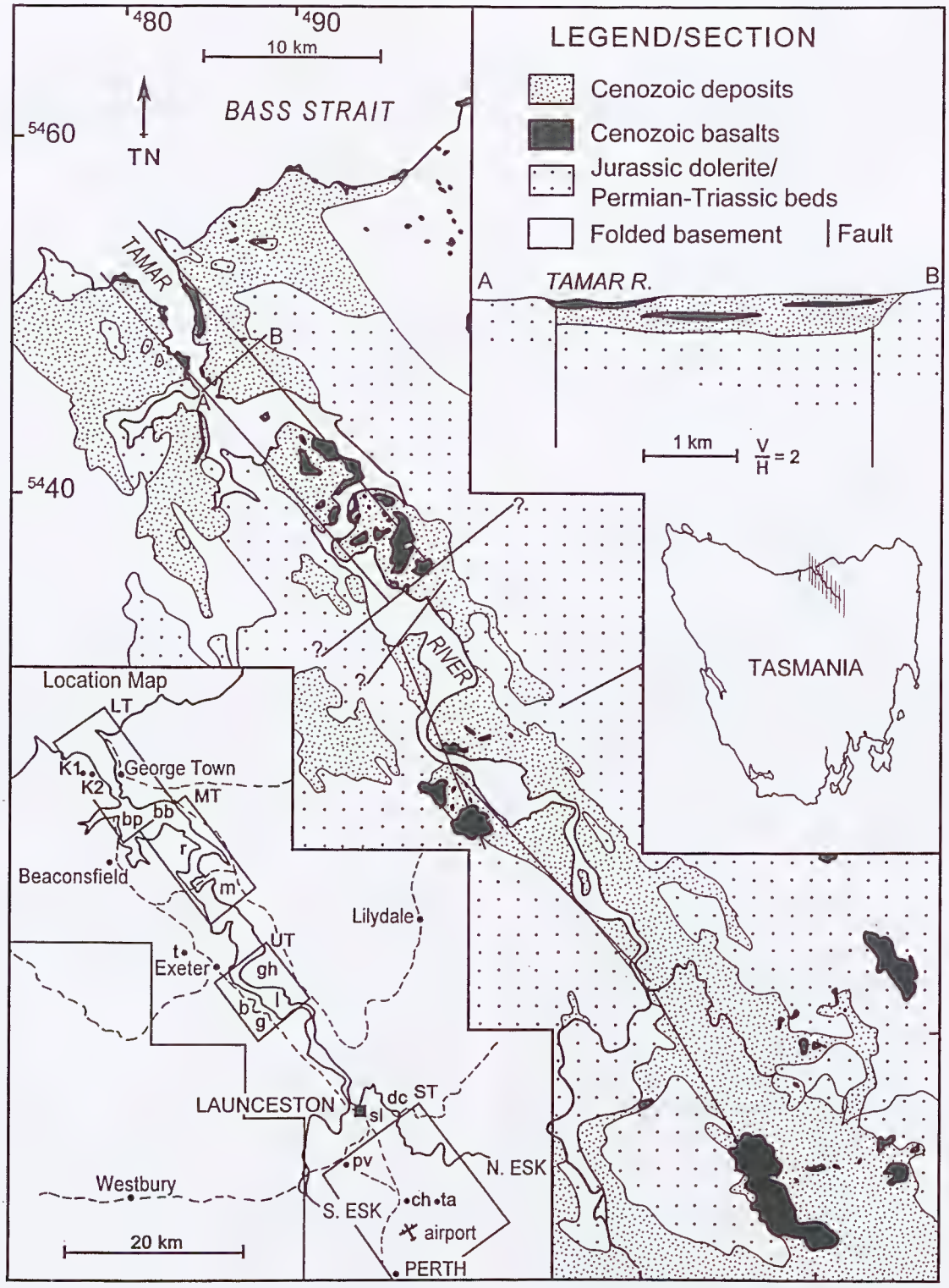

FIG. 1 — General geology, Tamar Trough, showing Cenozoic sedimentary deposits and basalt exposures, within the older rocks. The top right inset shows a stratigraphic legend, a Trough section (based on Leaman et al. *1973) and the Trough location in Tasmania. The bottom left inset shows the main drainages, towns and roads (dashed lines) in the study area, including the South Tamar (ST), Upper Tamar (UT), Middle Tamar (MT) and Lower Tamar (LT) areas. Other cited sites include Cocked Hat Hill (ch), Talisker (ta), Prospect Vale (pv), St Leonards (sl), Distillery Creek (dc), Legana (l), Grindelwald (g), Bradys Lookout (b), Gaunts Hill (gh), Tamerton (t), Murphys Hill (m), Rowella (r), Bell Bay (bb), Beauty Point (bp), Kelso (K).*

for Beaconsfield (Gee & Legge 1971), Frankford (Gulline 1973), Launceston (Longman *et al.* 1964) and Longford (Blake 1959), the 1:100 000 Longford Basin Map (Matthews 1974) and more recent 1: 25 000 mapping partly in progress. Grid references are based on the Australian Geodetic Datum {1966}, Grid Zone Designation 55G, with 100 000 metre square identification letters.

A gravity survey of the Tamar region showed the Tamar structural zone was a prominent down-faulted feature (Leaman *et al.* 1973). Sheets of Jurassic dolerite intruded into

Permo-Triassic sedimentary beds dominate the geological framework of the Tamar Trough, with older Palaeozoic basement rocks only exposed beyond the flanks of the structure. Cenozoic sedimentary beds and interbedded basalts occupy the main part of the Trough, along with a range of bauxitic and ferricrete deposits which developed on some horizons. The exposures are partly blanketed by alluvium, talus, landslip and soil deposits related to the more recent erosive process along the Tamar drainage system. Minor wind blown siliceous sands extend in from the Tamar mouth as far as Bell Bay and also occur south of Launceston.

Trough Structure

The Tamar Trough represents part of the faulting and uplift that led to significant erosion of parts of the Tasmanian highlands during its Late Cretaceous/Early Cenozoic history (Gleadow 1996, O'Sullivan *et al.* 2000). It links into the structural evolution of the Bass Basin (Cummings *et al.* 2001), along the Moyston-Tamar Fault Zone, a northwest-trending, broad basement fracture system (Blevin 2003). The tensional rifting that developed along the Tamar Trough lies east of the Mid-Devonian boundary between the East and West Tasmanian terranes (Reed *et al.* 2002). This boundary was thought to be a transcurrent fault concealed beneath the Tamar Trough (Williams 1979), but more recent ideas suggest that it marks a series of east dipping thrusts coming to the surface between Beaconsfield and Port Sorell (Elliot *et al.* 1993, Leaman *et al.* 1994, Reed *et al.* 2002). The structure lies between a down-warp of the mantle (Moho) under the West Tasmania terrane (Rawlinson *et al.* 2001) and a change in basement lithosphere under the East Tasmanian terrane (Kennett *et al.* 2004), but has no direct expression in the underlying lithosphere imaged by Rawlinson & Kennett (2006). The Moho lies between 29 km and 32 km below the Tamar Trough and shallows towards Bass Strait (Clitheroe *et al.* 2000). The Tamar region presently shows moderately high surface heat flow (85–95 m Wm^{-2}; O'Sullivan & Kohn 1997, O'Neill *et al.* 2003) and is underpinned by a moderately slow upper mantle shear-wave (thermal) structure (Kennett 2003, Kennett *et al.* 2004). The lithosphere here lies on the outskirts of a dormant mantle plume in the asthenosphere under Bass Basin, which acted as a trigger for hotspot volcanism along eastern Australia (Sutherland 2003) and is imaged down to ~ 650 km depth (Montelli *et al.* 2004). The crust here, however, is presently under compression with a mean horizontal stress maximum along a WNW-ESE direction (Clark & Leonard 2003).

Palynology Zones

The sedimentary beds within the Tamar Trough date back through several assigned palynological zones, with macro-plant fossils only playing a minor role in correlations (Jordan & Hill 2002). In a general way, the sedimentary units at and below the present Tamar River level become older upstream towards Launceston and younger downstream. Palaeocene beds are found at 60 m above sea level (ASL) at Launceston, although topographic distribution may be affected by growth faulting. The oldest palynoflora in drill cores can be assigned to the *Forcipites longus* Zone (Late Cretaceous into Palaeocene). South of Launceston, Palaeocene and Early Eocene deposits underlie what may be an erosion surface at the base of the Lower or Middle *Nothofagidites asperus* Zone with Eocene micro-flora (Stover & Partridge 1973, Bigwood *et al.* 1988). Above Rose Rivulet, basalt flows and conglomerates with basalt clasts occur here within or above the current Lower *N. asperus* Zone (Middle Eocene to Early Oligocene). Palaeocene palynoflora found in the eastern Tamar estuary opposite Legana belong to the *Lygistepollenites balmei* Zone. In cliffs on the western side at Legana, however, the listed palynoflora can be assigned to the Early Eocene Middle or Upper *Malvacipollis diversus* Zone (Bigwood *et al.* 1988). The ages adopted for the palynology zones are those proposed for the offshore Gippsland Basin by A.D. Partridge, which were presented by MacPhail (1999).

The *N. asperus* Zone palynofloras occur north of Legana within the older Early Eocene sedimentary sequence above Windermere and may represent younger channel deposits (Wells 1988), although stratigraphic inversion of palynofloras and potential block slides produce uncertainties in interpretations here. Further north, in the Long Reach-East Arm area, the oldest sedimentary beds found at river level belong to an undifferentiated Upper *M. diversus* Zone to *Proteacidites asperopolus* Zone interval (Early to Middle Eocene) and include interbedded basalt. Closer to the Tamar mouth, near Bell Bay, the palynofloras under basalt flows lie below sea level (BSL) and belong to Lower-Middle *Proteacidites tuberculatus* Zone (Oligocene), which occurs within a superimposed channel cut in pre-*N. asperus* Zone beds. Although the Jurassic dolerite basement is deepest here (250 m BSL), the Palaeocene sedimentary interval is either absent or very much reduced in thickness.

The palynology zones used in this study are correlated within a regional geochronology linking the Gippsland Basin sequence to Age (Ma BP), Sea Level Curves, Australian and International Biozonations (spores & pollens, dinocysts & acritarchs, benthic foraminifera, planktonic foraminifera, nanoplankton), Magnetic Polarity and the Geological Time Scale (Glenn *et al.* 1999). Care is needed to translate the Lower *Notofagidites asperus* zone as used by Stover & Partridge (1973) into later current usage (Bigwood *et al.* 1988; MacPhail 1999), where the original L. *N. asperus* Zone has been divided into new Lower and Middle zones.

BASALT SETTINGS

The basalt flows and intervening sedimentary beds appear in four principal areas (fig. 1), with each area including centres of volcanism from which flows extended for distances of 5–10 km. Only some feeders are known for the lavas that erupted within the Trough. One basalt plug was mapped outside the Trough at Supply Creek (Gulline 1973) and was sampled in this study as a potential lava source ("Tamerton" plug). Total magnetic intensity images derived from aeromagnetic surveys (with 200 m line spacings) indicate that although some basalt flows have normal polarity, many are reversely polarised, particularly in the Middle, Upper and South Tamar sections (pl. 1).

Basalt sampled in new exposures and drill cores since the earlier studies, including that intended for age-dating and chemical analysis, was thin-sectioned for detailed microscopic examination (pl. 2) and description (appendix A). Adjacent basalt flows in the Longford Basin (Matthews 1983) were also analysed for comparison with the Tamar Trough basalt flows (appendix B).

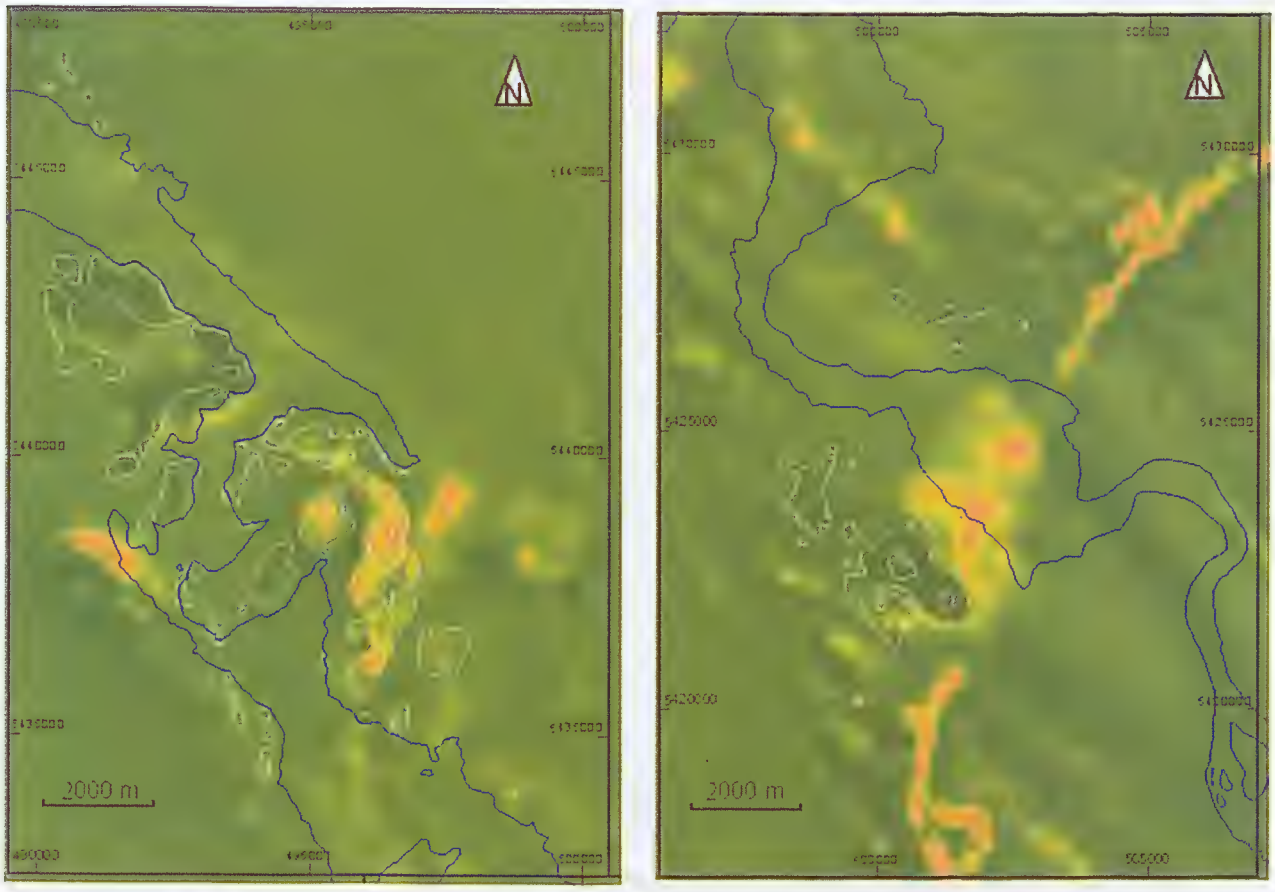

PLATE 1

Tamar Trough total magnetic intensity images, derived from Western Tasmanian Regional Minerals Program aeromagnetic surveys, 200 m line spacing 2001–2002. A. Middle Tamar. B. Upper Tamar. Basalt exposures have white outlines, while the Tamar River has blue outlines. Anomalies that can be linked to basalt include negative anomalies (darker green areas) that suggest reversed polarity of remanent magnetization, while positive anomalies (orange) suggest normal polarity. Some other anomalies related to depth to Jurassic dolerite component of basement are visible in both images. Some strong positive anomalies of uncertain origin may be related to dolerite intrusive structure and composition.

South Tamar Area

South of Launceston, a massive alkali basalt flow up to 40 m thick with reverse magnetic polarity extends south from a plug rising to 221 m ASL at Cocked Hat Hill, Bredalbane. It continues under Launceston airport southward down to 150 m ASL where it diverted the South Esk River course. The plug intrudes strata belonging to the *N. asperus* Zone and the associated flow overlies lignites with a Lower *N. asperus* Zone micro-flora. It is unclear on present exposures whether the flow base rests on an erosional interval.

The Cocked Hat Hill plug (EQ 16105033, 180 m ASL) was selected as the most significant basalt in the area for K-Ar and Ar-Ar dating. Several smaller flow and plug remnants of diverse petrology occur northeast of the main flow (Sutherland 1969 and this paper). These include basanites and alkali basalts that erupted from vents around the Talisker-Corra Linn area which infill drainages cut into Early Eocene beds. Basanite resembling that at Talisker forms flow remnants to the northeast and as far south as the South Esk Bridge at Perth (EP 151963, 140 m ASL) and as far west as Newry in drill cuttings (EP 10259735, 140 m ASL), 11 km from Talisker. Some olivine nephelinite and glassy basanite remnants lie respectively near Dunedin Farm and Distillery Creek east of St Leonards, whereas olivine tholeiite remnants at 215 m ASL at Abels Hill near St Leonards overlie quartz gravel beds that rest on Middle-Late Eocene siltstones (Sutherland 1969). Olivine basalt transitional between alkali and tholeiitic types (pl. 2) overlies clayey sandstone and silty claystone beds at 180 m ASL in a small valley-fill exposed in the new Bass Highway near Prospect Vale (EQ 104066). Most of these basalts have very fine grained or glassy groundmasses and are not suitable for dating.

Upper Tamar Area

North of Launceston, massive alkali basalt flows form prominent remnants above Rosevears on the West Tamar and extend from the western shores to 200 m ASL above Bradys Lookout and onto Grïndelwald plateau above the Loch Lea-Strathlyn area, where water bores indicate a 100 m thick capping flow. Similar, lesser flow remnants on the opposite eastern shore rise above Windermere to cap Gaunts Hill at 160 m ASL. The number of flows is uncertain as the basalts all show reverse magnetic polarity (pl. 1), but two distinct basalt types were recognised in western exposures, coarse alkali basalt-hawaiite (pl. 2B) and fine grained basanite (pl. 3C). Excavations in 2003 at Rosevears Estate winery at 120

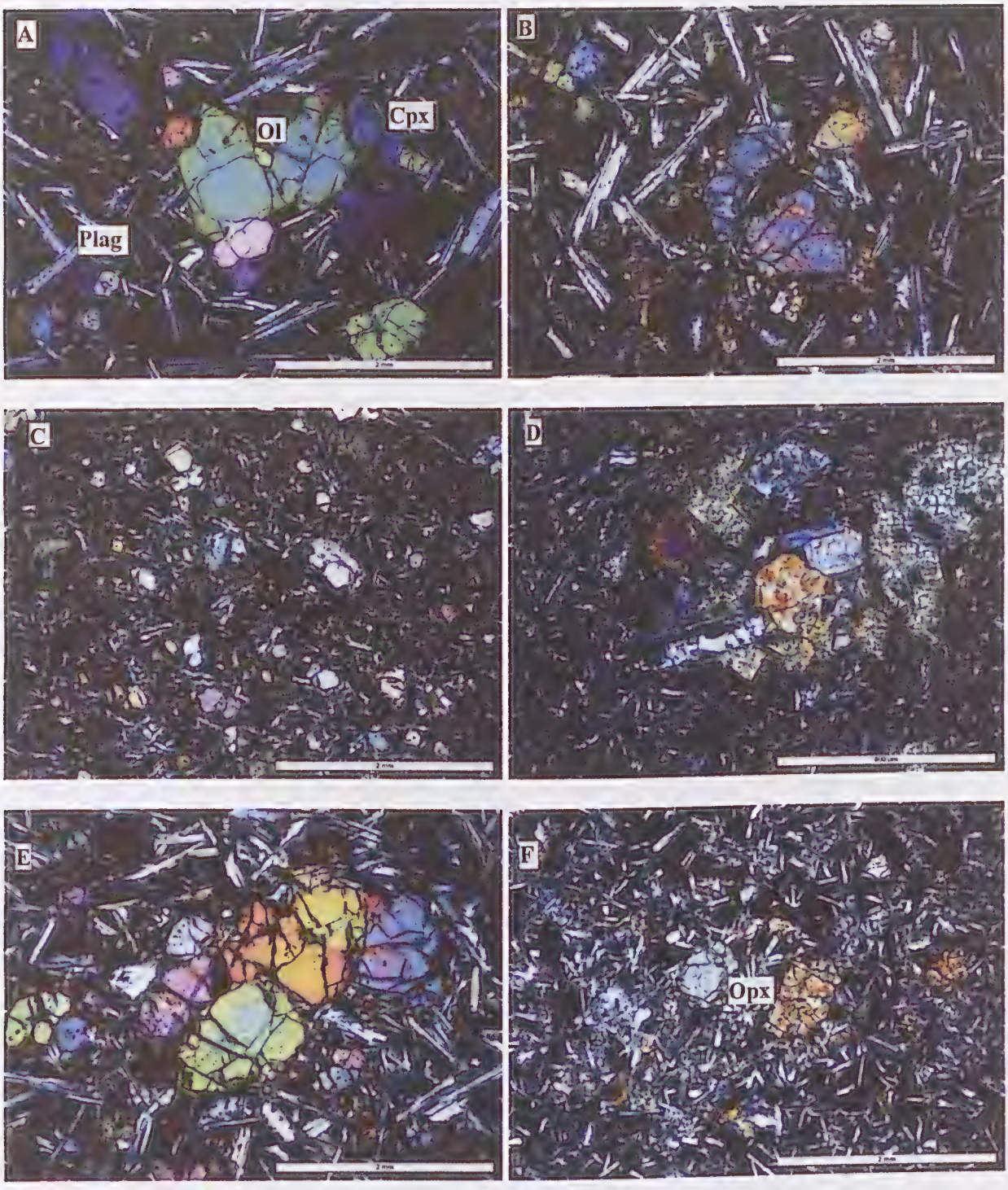

PLATE 2

Photomicrographs of Tamar basalt thin sections. A. Prospect Vale, transitional olivine-basalt. B. Coarse alkali olivine basalt, Rosvears Estate, Strathlyn. C. Basanite, Rosevears Estate, Strathlyn. D. Chilled vesicular hawaiite, Rowella DDH 1. E. Coarse hawaiite, Rowella DDH 2. F. Quartz tholeiite, Tamerton' basaltic' plug. All microphotographs taken with crossed polars. All scales are 2 mm, except for D at 0.5 mm. Photos: I. T. Graham.

m ASL exposed a vertical contact of fine grained basanite with vertical cooling columns abutting slightly weathered coarse alkali basalt (EQ 500700 5423200). Underlying strata here lack palynological assignment, but Early Eocene beds are known to the south and east at Legana and Gaunts Hill. The Gaunts Hill basalt may occupy a channel cut into the older sedimentary beds as an explanation for the *N. asperus* Zone deposits found above Windermere. To resolve the age of the Rosevears basalts and the underlying strata, and to assist correlations with the Windermere-Gaunts Hill section, coarse and fine grained basalts in the Loch Lea-Grïndelwald section were selected for K-Ar and Ar-Ar dating.

Middle Tamar Area

Basalt crops out between Deviot and Rowella on the western Tamar shore and from Craigburn to East Arm on the eastern shore. The exposures extend from river level up to 180 m ASL on Murphys Hill, east of Craigburn and include hawaiite, basanite, olivine nephelinite and a transitional olivine basalt plug (Sutherland 1969). A western massive hawaiite flow descends below river level and was drilled at Rowella (DDH 1 and 2), where it lies within strata of Upper *M. diversus* Zone or *P. asperopolus* Zone age. The basalt top showed some vesicularity, with no obvious baking of the overlying mudstone (DDH1), suggesting it forms a chilled flow top (pl. 2D) of a coarse flow (pl. 2E), rather than representing an intrusion. This makes it the oldest basalt recorded in the Tamar Trough, marking the drill core (DQ 930413) as a prime target for K-Ar and Ar-Ar dating.

The eastern flows occupy channels cut into similar aged beds to those dated at Rowella. The massive hawaiite that caps Murphys Hill through to East Arm, however, is normally magnetised, unlike the underlying Spring Bay olivine nephelinite and the Rowella hawaiite, which show reverse polarity (pl. 1). The Murphys Hill hawaiite also abuts a dolerite-clast conglomerate that contains rare basalt clasts, so the evidence clearly suggests different episodes of hawaiite extrusion. Dolerite-clast conglomerates form extensive lenses within the sedimentary beds east of the basalts from East Arm to Hillwood, which may indicate a re-routing of palaeodrainage. The upper hawaiite exposed in the Batman Highway road cuts was sampled for K-Ar dating (DQ 965392, 100 m ASL) not only to check the separate hawaiite ages, but also to provide some age control on dolerite-clast conglomerate deposition.

A small 'basaltic' plug (pl. 2F) mapped near "Tamerton" above Supply River (DQ 920302, 80 m ASL) was sampled for K-Ar dating in case it formed a potential eruptive site for flows to enter the Tamar Valley through an erosional low south of Loira.

Lower Tamar Area

Low-lying basalt flow remnants extend along the Tamar shores from south of Bell Bay on the east and from south of Beauty Point on the west to outlet at Tamar Heads between Low Head and West Head. The flows include a lower hawaiite with a base that descends from > 46 m ASL to > 18 m BSL. The base was intersected in Bell Bay drill cores where it overlies unweathered sedimentary beds related to the Lower-Middle *P. tuberculatus* Zone (Oligocene). The flow was also drilled south of George Town (Tamar Avenue DDH) where 20 m of basalt was intersected overlying sedimentary beds at ~ 5 m ASL (DQ 485000 5447000). A sample of this core retained in the Tasmanian Museum collection was selected for K-Ar dating to test the palynological correlation.

An upper transitional olivine basalt descends from a base at > 30 m at Bell Bay to ~ 15 m ASL at Beauty Point. It overlies interbasaltic strata and possibly continues through Kelso, west of the lower basalt, as similar olivine basalt was intersected in Kelso Drill Hole DDH 2 (DQ 481400 5449100) between 4.4 to 7.3 m depth where it overlies 7 m of carbonaceous clay and siltstones and deeper flows (Everard 1990). The Kelso drill holes penetrated the deeper flows between 21 to 60 m depth (DDH 1) and 14 to 33 m depth (DDH 2) where they show a distinct glassy nature (Everard 1990). These basaltic flows are interbedded with thin tuffs, tuffaceous sediments and non-volcanic beds and indicate multiple explosive eruptions. The basal beds (23 m thick in DDH 1, 9 m thick in DDH 2) contain decomposed dolerite fragments before solid dolerite is reached at 85 m (DDH 1) and 41 m (DDH 2) depth. Although the basalt samples were unsuitable for radiometric dating, the rare carbonaceous sediments provide some palynological control for these sections.

Samples from DDH 1 (DQ 819489) from horizons (54.8 m depth) between the deeper flows and from DDH 2 (12.5 m depth) from horizons between the highest and deeper flows contain spore assemblages no older than the Lower *P. tuberculatus* Zone. The lack of species that first appear in the base of the Middle *P. tuberculatus* Zone in the Gippsland Basin sequence suggests an Oligocene age for the Kelso sections, in keeping with the Lower-Middle *P. tuberculatus* Zone age for the Bell Bay basalt section.

ANALYTICAL METHODS

K-Ar Analysis

The K-Ar isotopic age determinations were made at CSIRO Petroleum, Bentley, Western Australia (table 1). Samples were split and crushed in a ring grinder with chrome steel barrel into a <500 µm fraction. The K content was determined by atomic absorption spectrophotometry (Varian AA20) using Cs at a concentration of 1000 ppm for ionisation suppression. Sample aliquots were dissolved with hydrofluoric and nitric acid (Heinrichs & Herrmann 1990) and solutions were diluted for the atomic absorption analysis. Ar isotopic determination followed Bonhomme *et al.* (1975) with the samples pre-heated to minimise atmospheric Ar adsorbed onto the mineral surfaces. Argon was extracted from the mineral fraction by fusing the sample with a vacuum line serviced by an on-line ^{38}Ar spike pipette. The isotopic composition of the spiked Ar was then measured using an on-line VG3600 mass spectrometer. The ^{38}Ar spike was calibrated against the standard biotite GA1550 (McDougall & Roksandic 1974). After fusion of the sample in a resistance furnace, the released gases were purified using a Cu_2O getter and then two Ti getters. Blanks for the extraction line and mass spectrometer were systematically determined and the mass discrimination factor was determined periodically by airshots. During analysis, international standards provided calibration. The error for the Ar analysis is below 1%. The K-Ar calculation used constants after Steiger & Jäger (1977). The age uncertainty includes the errors during sample weighting, $^{38}Ar/^{36}Ar$ and $^{40}Ar/^{38}Ar$ measurements and K analysis.

^{40}Ar-^{39}Ar analysis

This follows typical ^{40}Ar-^{39}Ar dating procedures (McDougall & Harrison 1999). A concentrate of separated feldspar was cleaned and wrapped in aluminium foil along with biotite standard HD-B1 (24.21 ± 0.32 Ma; Hess & Lippolt 1994) to monitor the neutron flux gradient. The package was irradiated in the McMaster University Nuclear Reactor, Hamilton, Canada.

For infra-red laser step-heating, the mineral separate was baked to remove adsorbed atmospheric argon. A 110 W Spectrum Laser system continuous wave Nd-Y-Al-garnet

(σ=1064 nm) laser was used to treat the sample. After removing active gases the remaining noble gases were equilibrated into a Mass Analyser Product 215-50 static mass spectrometer (MS) with a multiplier detector. The Ar sensitivity of the MS multiplier detector was 2.71 x 10^{-10} cm^3/Volt. A Lab View program was used to measure isotope peak masses from 35–41 (10 times) in sequence lasting ~ 15 minutes, via a peak hopping routine. Blank analyses were run before and after.

Age calculation (table 2) involved extrapolating peak intensities back to the inlet time and correcting for extraction line blanks, MS backgrounds, MS discrimination ($^{40}Ar/^{36}Ar$ ratio of 281.0) and reactor interference. The Ca and K correlation factors in the data reduction were $^{39}Ar/^{37}Ar_{Ca}$ = 0.00065, $^{36}Ar/^{37}Ar_{Ca}$ = 0.000255 and $^{40}Ar/^{36}Ar_{K}$ = 0.0015. Errors quoted are 1 σ and Ar-Ar ages (fig. 2) were calculated using decay constants of Steiger & Jäger (1977). Weighted mean ages were calculated (2σ errors) using the Ludwig (2001) Isoplot program.

Whole rock chemistry

The basalt nomenclature used here follows that for Australian basalts defined by Johnson (1989); while the alternative recommended International Union of Geological Science nomenclature (Le Maitre 1989) is covered by using the petrological fields in figure 3. The basalts are dominantly slightly evolved alkali basalts and hawaiites, with subordinate olivine nephelinites, basanites, transitional olivine basalts, olivine tholeiites and quartz tholeiites.

Major and minor elements of basalt samples, listed in table 3 and for Kelso tholeiite in table 5, were made on fresh samples crushed in a steel jaw crusher and determined by X-ray fluorescence (XRF) methods on glass discs prepared by standard techniques at Mineral Resources Tasmania (MRT) Laboratories, Hobart. FeO was determined by titration and CIPW norms were calculated for the basalts using a Fe_2O_3/FeO ratio of 0.2 as recommended by Johnson (1989). The CO_2 was determined by gravimetric methods, while H_2O (+) was calculated from loss-on-ignition (LOI) after adjusting for FeO, CO_2 and SO_3. The trace element values come from XRF analyses using conventional methods and rock standards on pressed pellets. The other major, minor and trace elements for basalts in table 4 and the "Tamerton" tholeiite in table 5 were analysed at the XRF and XRD Facility, University of Pretoria, South Africa. Samples were ground in a tungsten carbide mill, roasted at 1000°C to determine LOI, then fused with lithium borate into glass beads which were analysed by XRF using an ARL 9400 X 1(+) spectrometer set up. Another aliquot of sample was pressed into a powder briquette for selected trace element analyses. Precisions for XRF major element oxides (table 4) were SiO_2 less than 0.3%, TiO_2 < 5%, Al_2O_3 < 1%, Fe_2O_3 < 3%, MnO <17%, MgO < 7%, CaO < 12%, Na_2O <2%, K_2O < 1%, P_2O_5 < 4% and LOI 3% and for XRF trace elements were Ni <1%, Cr <4%, Co <16%, Sc <1%, V <7%, Y <11%, Rb < 1%, Sr <2%, Ba <1%, Zr <8%, Nb <15%, La <15%, Ce <1%, Pb <2%, Ga <10%, Th <12%, U <1%, Cu <25%, Zn <1%. Mg values were calculated as 100 $Mg/Mg+Fe^{2+}$ (at Fe_2O_3/FeO = 0.2).

The trace and rare earth element (REE) values (table 4) were measured by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) techniques at the Geology Department, University of Cape Town, Rondebosch, South Africa. Dissolution of samples used a standard acid digestion procedure before analysis on a Perkin Elmer Sciex Elan 6000 ICP-MS. The instrument operating conditions were optimised to minimise the formation of doubly charged ions and oxides. Interference corrections were made for isobaric interferences and doubly charged ion and oxide interferences (particularly on REE). Both within-run and duplicate analysis precisions were mostly between 2% relative and always < than 3% relative (1 sigma).

RESULTS

Geochronology

The K-Ar dates (table 1) provide a wide range of ages. Some are minimum results due to some late-stage glass or alteration in those rocks. However, the dates clearly establish several well-separated basaltic events within the Tamar Trough. The youngest dated basalt is represented by the Late Oligocene age for the Lower Tamar hawaiite at George Town (24.7 Ma). It underpins the Bell Bay-Beauty Point basalt sequence and is

TABLE 1
K-Ar dating results, Tamar Trough basalts

Sample no./ (Rock type)	K (%)	Rad ^{40}Ar (mole/g)	Rad ^{40}Ar (%)	Age (Ma)	Error (Ma)
Y1295 (TM) Hawaiite	0.88	9.8948 x 10^{-11}	43.16	24.72	± 0.53
DR16808 Hawaiite	1.04	5.3408 x 10^{-11}	45.04	29.37*	± 0.87
DR10499 Hawaiite	1.05	5.9784 x 10^{-11}	64.71	32.53*	± 0.67
DR 17070 Basanite	1.15	5.9291 x 10^{-11}	71.73	33.74*	± 0.70
ROW (TMR) Hawaiite	0.83	6.8126 x 10^{-11}	61.10	46.66	± 1.02
TAM (AM) Tholeiite	0.71	2.0478 x 10^{-10}	91.07	159.28*	± 3.17

* Probable minimum age due to presence of minor mesostasis, glass or alteration.

TM (Tasmanian Museum sample), TMR (Tasmanian Mineral Resources sample), DR and (AM) Samples are Australian Museum Collection material.

Y1295 (TM). Flow, Tamar Avenue DDH, Georgetown (Beaconsfield DQ 85034469).

DR16808. Plug, Cocked Hat Hill, 180 m ASL (Longford EQ 16150330).

DR10499. Flow, Batman Bridge Highway, 100 m ASL (Beaconsfield DQ 96503920).

DR17070. Flow, Loch Lea, West Tamar Road, 75 m ASL (Launceston EQ01052325).

ROW (TMR). Flow, Rowella DDH2, 104.5 m depth (Beaconsfield DQ 93004130).

TAM (AM). Plug, "Tamerton", Supply River, 80 m ASL (Frankford DQ 920302).

TABLE 2
^{40}Ar-^{39}Ar analyses, Tamar Trough basalts

Step	Age (Ma)	$^{40}Ar^*/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{38}Ar^*/^{39}Ar$	$^{37}Ar^*/^{39}Ar$	$^{39}Ar(10^{-12}cm^3)$	$^{40}Ar^*\%$	$^{36}Ar/^{39}Ar$
Pegmatitic hawaiite, Grïndelwald plateau, Y1205 (Feldspar separate 459 KF).								
1.	30.07±1.50	4.75±0.24	6.33±0.06	0.01637±0.00039	3.50273±0.39007	3.48±0.007	24.90	0.39007±0.00533
2.	37.13±0.31	5.88±0.04	7.19±0.01	0.01637±0.00007	3.72159±0.06819	20.60±0.014	18.23	0.06819±0.00444
3.	36.59±0.49	4.80±0.07	7.08±0.01	0.01323±0.00013	4.25931±0.02558	20.20±0.013	18.17	0.02558±0.00435
4.	39.01±1.99	6.18±0.32	7.48±0.05	0.01523±0.00071	3.59482±0.10594	3.83±0.006	17.33	0.10594±0.00439
5.	32.16±2.33	5.09±0.37	6.27±0.01	0.01416±0.00025	2.96145±0.03374	5.40±0.005	18.90	0.03374±0.00401
6.	41.27±9.38	6.55±1.50	7.78±0.02	0.01149±0.00102	3.59157±0.13657	1.33±0.003	15.85	0.13657±0.00417
7.	40.08±1.38	6.35±0.22	7.60±0.03	0.01430±0.00073	3.58780±0.13927	1.85±0.003	16.41	0.13927±0.00422
8.	36.66±1.11	5.81±0.17	8.12±0.03	0.01382±0.00059	3.74168±0.07911	2.31±0.006	28.50	0.07911±0.00784
9.	37.57±0.20	5.95±0.01	7.12±0.01	0.01546±0.00028	3.07406±0.01922	9.71±0.014	16.43	0.01922±0.00396
Total gas age 36.73±3.38 Ma						68.70		
Plateau Ar-Ar age 36.98±0.22 Ma with 74.8% of ^{39}Ar								
Hawaiite, Cocked Hat Hill, CCH (TMR) (Feldspar separate 414 KF)								
1.	30.68±0.68	4.85±0.10	49.59±0.30	0.05622±0.00032	5.81723±0.24164	10.939±0.005	90.22	0.15141±0.00089
2	24.92±0.17	3.93±0.02	50.45±0.07	0.04391±0.00006	6.86041±0.11141	2.026±0.003	92.20	0.15742±0.00021
3.	32.07±2.32	5.07±0.37	58.92±0.09	0.04858±0.00024	9.91998±0.95496	11.961±0.018	91.39	0.18224±0.00127
4.	31.59±3.95	5.00±0.63	44.01±0.06	0.03845±0.00029	9.52268±1.01863	22.918±0.029	88.65	0.13202±0.00214
5.	31.82±4.26	5.03±0.68	46.97±0.06	0.04026±0.0030	10.48736±1.07583	21.405±0.024	89.28	0.14191±0.00230
6.	32.77±5.91	5.18±0.94	35.63±0.08	0.03284±0.00055	9.44133±1.55320	15.295±0.034	85.45	0.10302±0.00320
7.	37.28±3.37	5.90±0.54	27.74±0.02	0.02667±0.00031	6.44878±0.89273	26.652±0.017	78.72	0.07390±0.00182
8.	35.48±2.35	5.62±0.37	22.29±0.02	0.02396±0.00025	5.13939±0.68285	25.414±0.014	74.80	0.05641±0.00127
9.	38.57±3.06	6.11±0.49	15.91±0.01	0.01811±0.00030	3.21887±0.88728	19.491±0.014	61.58	0.03315±0.00165
10.	37.27±1.94	5.90±0.31	13.83±0.02	0.01820±0.00021	1.98460±0.60079	16.472±0.018	57.32	0.02683±0.00104
11.	40.65±2.03	6.45±0.32	15.35±0.02	0.01890±0.00022	1.87399±0.62420	15.883±0.014	58.00	0.03012±0.00110
12.	41.64±2.13	6.60±0.34	15.36±0.02	0.01851±0.00023	1.79766±0.65412	15.167±0.014	57.00	0.02962±0.00115
Total gas age 34.56±4.59 Ma						193.64		
Plateau Ar-Ar age 36.92±0.46 Ma with 45.5% ^{39}Ar								

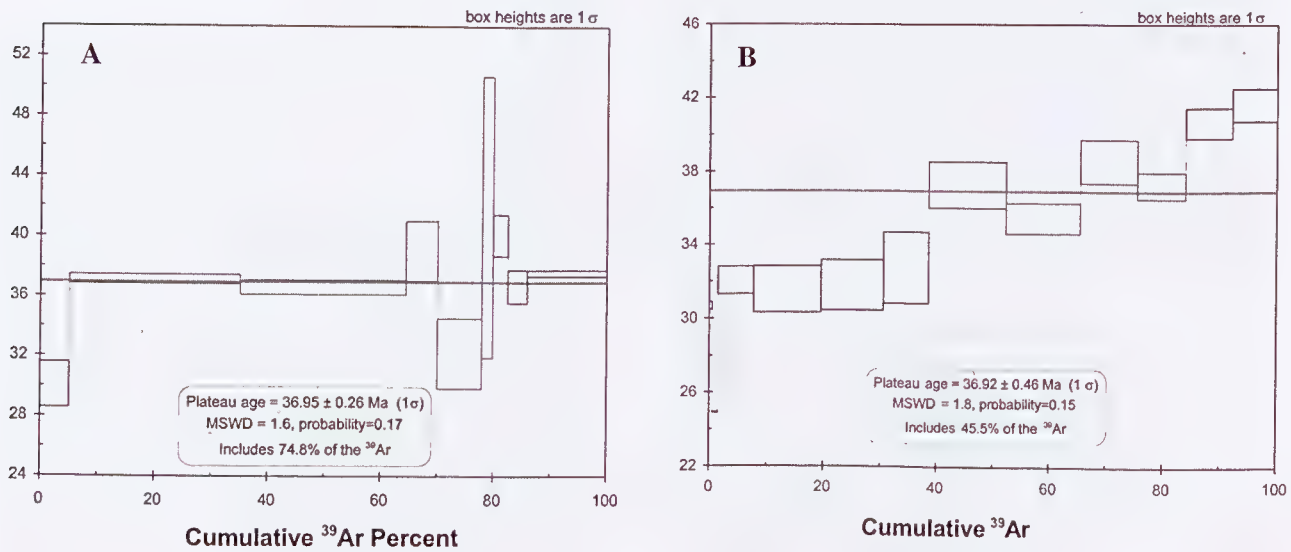
box heights are 1 σ
A
Plateau age = 36.95 ± 0.26 Ma (1σ)
MSWD = 1.6, probability=0.17
Includes 74.8% of the 39Ar
Cumulative 39Ar Percent
box heights are 1 σ
B
Plateau age = 36.92 ± 0.46 Ma (1 σ)
MSWD = 1.8, probability=0.15
Includes 45.5% of the 39Ar
Cumulative 39Ar

FIG. 2 — Step heating age spectra (apparent age versus cumulative ^{39}Ar released). (A) Strathlyn pegmatoidal hawaiite. (B) Cocked Hat Hill hawaiite.

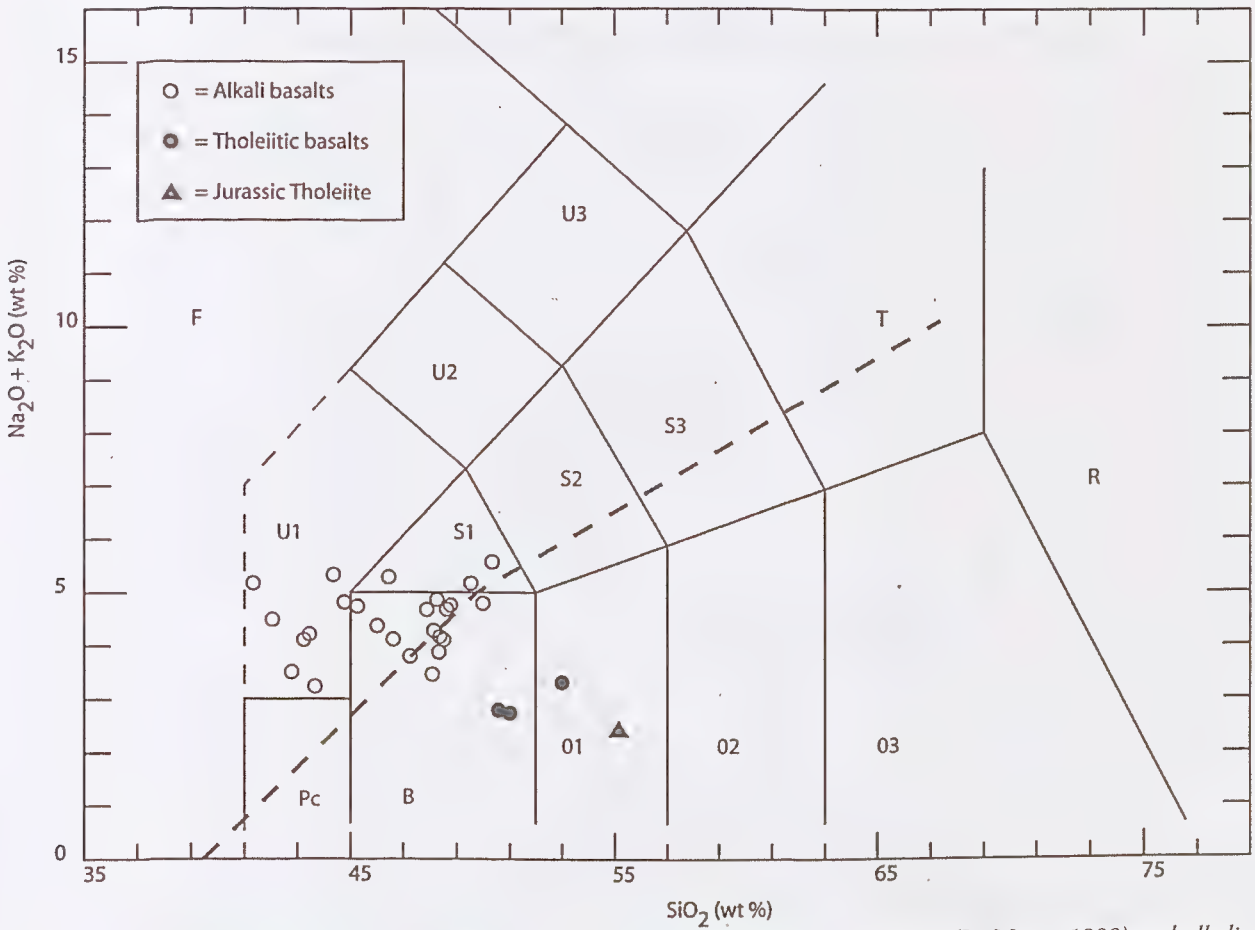

FIG. 3 — Silica against Total Alkalis plots for Tamar basalts related to IUGS basalt categories (Le Maitre 1989) and alkaline and subalkaline fields (Irvine & Baragar 1971). Occupied fields are: B basalt, U1 basanite, S1 trachybasalt/ hawaiite, O1 basaltic andesite.

compatible with the underlying Lower-Middle *P. tuberculatus* Zone (Oligocene) age sediments there and in the Kelso basalt sections to the east. This dates the diversion of the lower Tamar through Kelso as an Oligocene feature. The next group of ages lies between 29–33 Ma (Early Oligocene) from several places along the Tamar Trough. These ages are all consistent with their positions overlying or adjacent to sediments as old as or older than the *N. asperus* Zone (Early Oligocene-Middle Eocene). The higher level hawaiite capping Murphys Hill and the Batman Highway in the Middle Tamar at 32 Ma clearly post-dates earlier flows and Upper *M. diversus-P. asperopolus* Zone (Early-Middle Eocene) age sediments to the west. The Loch Lea basanite near Strathlyn in the Upper Tamar sequence at 34 Ma provides a minimum age for the sediments under the Grïndelwald basalt plateau and is compatible with the *N. asperus, M. diversus* and *L. balmei* Zones (Early Oligocene-Palaeocene) found in discrete sedimentary sections between Legana and Windermere. The oldest basalt flow dated in the Tamar sections is the Rowella hawaiite at 46.7 Ma. This Middle Eocene age is consistent with its interbedded position within Upper *M. diversus-P. asperopolus* Zone (Early-Middle Eocene) sediments and is also compatible with its position below erosional surfaces for further basalt infills extending up sequence from Spring Bay (nephelinite) to the 32 Ma Batman Highway hawaiite. The 'Tamerton' result at > 159 Ma clearly stands outside the Tamar Trough volcanism as a Jurassic event linked to the extensive dolerite intrusions and did not source any basalt within the Trough.

The follow up Ar-Ar dating on selected basalts (table 2) refines the K-Ar dating. This method was attempted on the Rowella hawaiite (K-Ar 46.7 Ma ± 1.0 Ma). The sample, however, only yielded very small amounts of gas, possibly due to contamination. Only five heating steps were possible on each separate split of the sample, which was insufficient to define satisfactory spectra. The best total gas age was 40.06 ± 1.60 Ma and is best considered a minimum age. The $^{40}Ar/^{36}Ar$ intercept in this sample is 165 ± 21, which suggests little or no excess Ar is involved. Thus, available data suggests the Rowella hawaiite is >40 Ma and that a more reliable date is the K-Ar age of 46.7 ± 1.0 Ma, which is compatible with the palynological age.

The coarse-grained Grïndelwald plateau hawaiite gave an Ar-Ar Total gas age of 36.7 ± 3.4 Ma and a plateau age of 37.0 ± 0.2 (459, fig. 2). Thus, the underlying sediments here are firmly *N. asperus* and older age zones. The age allows for alteration and/or erosion of the Grïndelwald hawaiite prior to contact with Loch Lea basanite as observed at Rosevears Estate. This relationship brackets the Loch Lea basanite to an age between 33.7 ± 0.7 Ma (K-Ar) and 37.0 ± 0.2 Ma (Ar-Ar). It also gives the Tamar drainage a reasonable period to down-cut and re-establish its course through the massive basalts that filled the Early Oligocene channel there. The Cocked Hat Hill hawaiite gave a total gas age of 34.6 ± 4.6 Ma and a plateau Ar-Ar age of 36.9 ± 0.5 Ma (414, fig. 4). The $^{40}Ar/^{36}Ar$ intercept is 283 ± 8, which suggests no excess Ar is present, as it is close to the

TABLE 3
Whole rock XRF element analyses (wt %, ppm) and CIPW norms, Tamar Trough basalts

Oxide	BA[1]	BA[2]	BA[3]	AB[4]	HA[5]	OB[6]	OB[7]	OT[8]	TH[9]
SiO_2	43.31	44.58	44.19	46.03	47.38	47.19	47.19	50.29	49.83
TiO_2	2.76	2.43	2.52	1.95	2.05	2.06	2.31	2.01	1.73
Al_2O_3	11.39	13.60	13.69	14.38	13.94	13.74	14.01	13.38	13.47
Fe_2O_3	2.51	2.40	6.22	1.68	2.61	1.37	3.60	1.66	1.16
FeO	9.89	9.50	6.39	9.31	8.46	9.44	9.51	9.31	11.10
MnO	0.17	0.18	0.19	0.16	0.17	0.16	0.16	0.15	0.16
MgO	11.49	10.86	9.70	10.17	9.43	9.84	7.80	9.14	8.27
CaO	10.21	9.62	10.24	9.54	8.75	9.25	8.04	8.55	8.97
Na_2O	3.54	3.28	3.27	2.93	3.12	2.80	3.21	2.71	2.45
K_2O	1.22	1.35	1.47	1.27	1.11	0.86	1.04	0.73	0.30
P_2O_5	0.75	0.53	0.74	0.44	0.51	0.48	0.45	0.33	0.26
H_2O+	1.60	1.54	1.23	1.60	1.86	1.82	1.80	1.11	1.22
CO_2	0.07	0.08	0.12	0.04	0.19	0.28	0.20	0.19	0.08
SO_3	0.02	0.00	0.06		0.11	0.02	0.07	0.05	0.11
Total	98.93	99.94	100.03	99.50	99.69	99.31	99.39	99.61	99.11
Mg value	66.55	66.20	62.98	66.40	66.35	64.75	65.97	64.04	58.89
CIPW anhydrous 100 wt % norms, calculated at Fe_2O_3/ FeO = 0.2									
Q									0.82
or	7.43	8.13	8.84	7.68	6.73	5.22	6.32	4.39	1.83
ab	9.35	12.64	11.39	18.38	26.92	24.36	27.92	23.31	21.23
an	11.92	18.72	18.68	22.81	21.27	23.03	21.38	22.58	25.39
ne	11.62	8.45	9.08	3.77	0.12				
di	28.39	21.27	22.82	18.31	16.05	16.91	13.63	14.92	14.99
hy						4.78	4.66	24.87	28.68
ol	21.01	21.92	19.54	21.49	20.94	17.79	17.25	2.55	
mt	3.07	2.91	2.99	2.71	2.72	2.69	3.21	2.70	3.04.
il	5.40	4.68	4.87	3.77	3.98	4.02	4.52	3.88	3.36
ap	1.81	1.22	1.71	1.01	1.20	1.13	1.04	0.79	0.61
An%	55.58	58.26	60.72	53.91	42.68	47.12	41.92	47.73	52.99
D.I.	28.40	29.22	29.31	29.83	33.77	29.58	34.24	27.69	23.06
Trace elements (ppm)									
Ni	320	220	210	190	200	200	195	230	250
Cr	390	290	220	350	290	330	260	340	350
Co	66	59	49	52	49	52	46	55	47
Sc	21	22	20	20	17	21	23	26	25
V	140	140	200	135	175	120	160	130	155
Ba	280	290	370	250	260	280	200	160	82
Rb	21	24	30	21	28	16	22	22	8
Sr	880	770	980	690	1150	780	490	370	270
Y	24	21	22	18	20	20	20	24	22
Zr	250	230	280	185	110	200	210	165	120
Nb	70	51	65	39	33	41	29	19	11
La	38	27	44	25	30	23	<20	<20	<20
Ce	76	69	100	55	73	63	45	30	<28
Nd	37	29	43	30	30	29	28	<20	<20
Pb	<10	<10	<10	<10	15	<10	18	<10	16
Th	<10	<10	19	<10	<10	15	<10	<10	<10
U	<10	<10	<10	<10	<10	<10	<10	<10	<10
Cu	51	64	66	53	33	40	53	46	82
Zn	145	115	130	100	105	120	130	135	120
Ga	23	22	23	20	22	21	24	22	18
Σ Inc.	797	591	499	612	559	603	524	851	672

Σ Inc. Sum of incompatible elements Ni, Cr, Co, Sc.

TABLE 3 cont.

Key element ratios									
Zr/Nb	3.57	4.51	4.31	4.74	3.33	4.88	7.24	8.68	10.91
La/Nb	0.54	0.53	0.68	0.64	0.91	0.56	>0.83	>1.05	>0.40
Ba/Nb	4.00	5.69	5.69	6.41	7.88	6.83	6.90	8.42	8.07
Rb/Nb	0.30	0.47	0.46	0.54	0.85	0.39	0.71	1.16	0.73
Ba/La	7.37	10.74	8.41	10.00	8.67	12.17	>10.00	>5.00	>4.10
La/Y	1.58	1.29	2.00	1.39	1.50	1.15	<1.00	<0.89	<1.11
Ce/Y	3.12	3.29	4.55	3.06	3.65	3.15	2.25	1.25	<1.56

1 Basanite (BA) Tasman Highway, Distillery Creek (Launceston EQ 212124).
2 Basanite (BA) Rosevears Estate, Strathlyn (Launceston EQ 006233).
3 Basanite (BA) Bridge, Midlands Highway, Perth (Longford EP 152962).
4 Alkali basalt (AB) Rosevears Estate, Strathlyn (Launceston EQ007232).
5 Hawaiite (HA) Cocked Hat Hill, Breadalbane (Longford EQ 1681 0365).
6 Ol-basalt (OB) Bass Highway, Prospect Vale (Launceston EQ 106068).
7 Ol-basalt (OB) Kelso DDH 2/7.0 (Beaconsfield DQ 814491).
8 Ol-tholeiite (OT) Abels Hill Road, St Leonards (Launceston EQ 179113).
9 Tholeiite (TH) Kelso DDH 1/51.6 (Beaconsfield DQ 819489).

TABLE 4
Comparative normalised analyses, hawaiite fractionation, Tamar Trough

Major & minor elements			CIPW (anhydrous) Norms*			Trace elements			Rare Earth Elements		
Oxide wt %	ROW	CHH	wt%	ROW	CHH	ppm	ROW	CHH	ppm	ROW	CHH
SiO_2	48.27	48.61	or	6.07	6.69	Ni	177	53.3	La	22.0	22.9
TiO_2	1.82	2.31	ab	24.98	29.05	Cr	348	152	Ce	43.6	51.0
Al_2O_3	14.41	16.31	an	23.38	24.82	Co	59	48.4	Pr	5.29	5.78
Fe_2O_3*	2.40	2.26	ne	-	1.37	Sc	23	17.1	Nd	22.6	24.4
FeO	8.64	8.13	ol	20.28	12.26	V	203	225	Sm	4.71	5.17
MnO	0.17	0.16	di	15.28	16.77	Rb	16.4	11.0	Eu	1.58	1.75
MgO	10.19	6.13	hy	2.88	-	Sr	605	608	Gd	4.74	5.05
CaO	9.01	9.81	mt	2.67	3.30	Y	18.7	17.9	Tb	0.67	0.72
Na_2O	2.93	3.70	il	3.48	4.42	Zr	141	167	Dy	3.82	4.01
K_2O	1.02	1.12	ap	1.02	1.34	Nb	36.4	40	Ho	0.72	0.74
P_2O_5	0.43	0.56				Ba	228	219	Er	1.87	1.89
L.O.I.	0.76	0.90				Hf	2.97	3.52	Tm	0.25	0.29
Total	100.05	100.00		99.95	100.00	Ta	3.28	3.30	Yb	1.57	1.48
Mg/ $(Mg+Fe^{2+})$%	66.5	55.9	An/ (Ab+An)%	46.8	45.8	Pb	2.75	2.51	Lu	0.23	0.21
						Th	3.02	2.85	ΣREE	114	126
Na_2O/K_2O	2.88	3.30	Σor,ab, ne (D.I.)	31.1	36.6	U	0.91	0.92	Cs	0.8	0.35
						Cu	49.8	62.3	ΣNi,Cr	525	205

*Calculated at Fe_2O_3/ FeO ~ 0.2
ROW Rowella, DDH2, 114.5 m depth (Beaconsfield DQ 930413).
CHH Cocked Hat Hill quarry, 180 m ASL (Longford EQ 16150330).
Analysts, XRF main elements, M. Loubser; ICPMS trace elements, A. Spath.

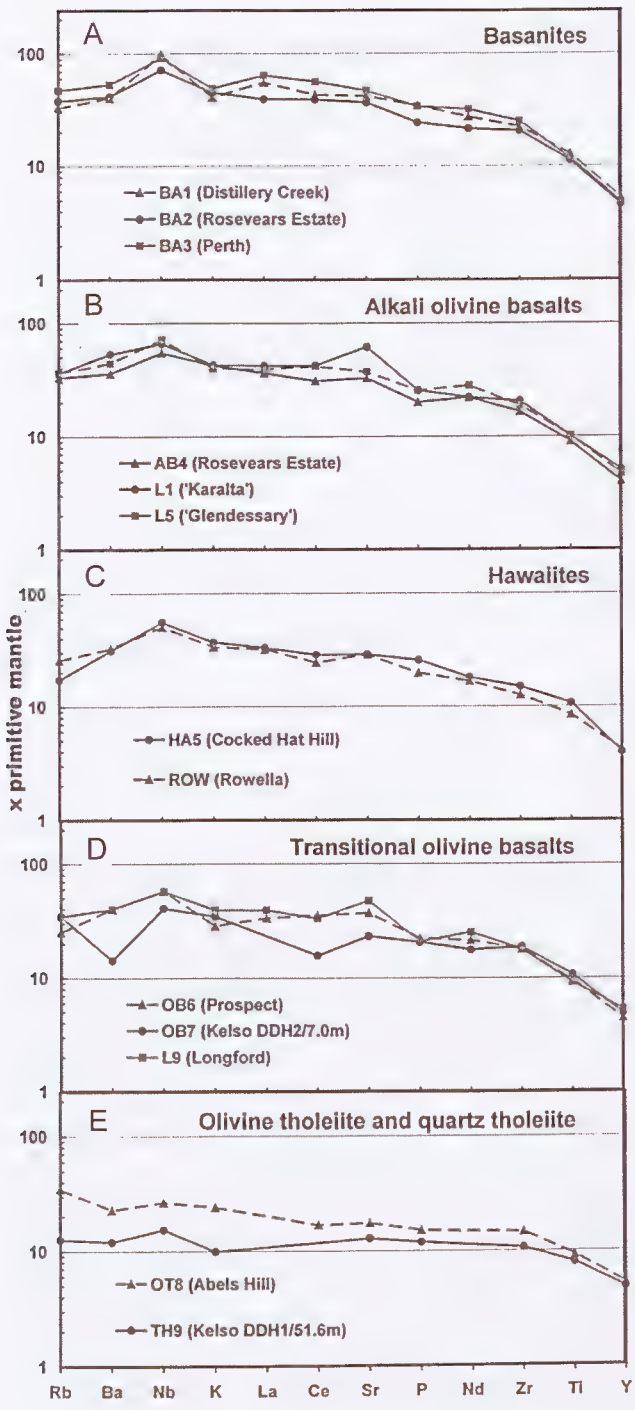

FIG. 4 — Primitive Mantle-normalised, multi-element plots, Tamar and Longford basalts (normalising values, after Sun & McDonough 1989). (A) Basanites, (B) alkali basalts, (C) hawaiites, (D) transitional Ol-basalts, (E) Ol-tholeiite, Q-tholeiite.

$^{40}Ar/^{36}Ar$ air ratios of 295.5. The Ar-Ar age matches the underlying Lower *N. asperus* Zone age and precludes any significant erosion between sediment deposition and hawaiite extrusion. It places the significant westward diversion of the South Esk through Cataract Gorge to the Launceston area to no older than Late Eocene time.

Basalt Geochemistry

The further basalt analyses (tables 3–5) confirm and expand the previously demonstrated petrological range and include olivine nephelinites and basanites (ne > 5%), alkali basalts, hawaiites and transitional olivine basalts (ne < 5%, hy < 10%) and olivine tholeiites (hy >10%) and quartz tholeiites (hy + Q). The alkaline rocks include near-primary to primary types (Mg values 65-67, An % 44-81, D.I. 27-34), with compatible element contents (Ni, Cr, Co, Sc) between 525 to 800 ppm, and moderately evolved equivalents (Mg values 56–63, An% 37–61, D.I. 29–38, compatible elements 265–500 ppm). The olivine and quartz tholeiites show mildly evolved parameters that typify such basalts in Tasmania (Mg values 58–62, An % 53–54, D.I. 23–24), but retain relatively high compatible element contents (670–850 ppm). The 'Tamerton' qtz tholeiite, now known to be Jurassic in age, is clearly more silica-rich (Q 19%) and calcic (An% 62) and relatively depleted in compatible elements (204 ppm), compared with the Cenozoic Tamar tholeiites. For total alkalis against SiO_2 (fig. 5), the basalts show a general decrease in alkali contents across the alkaline into the subalkaline fields. The bulk of alkali basalts are moderately sodic types (Na_2O/K_2O 2.2–3.8), while the Kelso tholeiites are distinctly low in K_2O (Na_2O/K_2O 8.2). A few Tamar alkaline rocks are less sodic in nature, particularly the highly undersaturated rocks in the St Leonards-White Hills area (Na_2O/K_2O 1.1–1.6; Sutherland 1969).

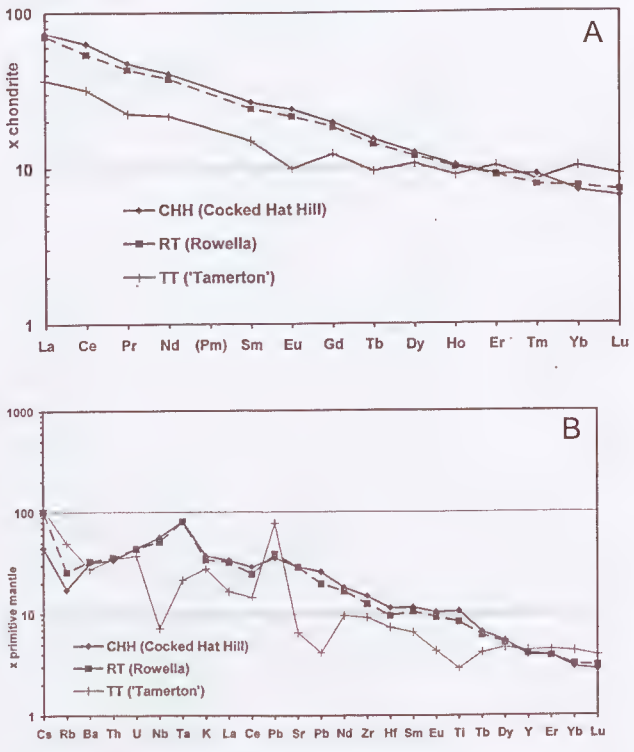

FIG. 5 — Normalised multi-element plots, Tamar alkaline basalts (Cocked Hat Hill, Rowella) and Tamerton quartz tholeiite. (A) REE. (B) Multi-elements. The Tamerton plots utilise unpublished ICPMS analyses (A. Spath, analyst). Chondrite normalising values are taken from Boynton (1984) and Primitive Mantle normalising values are after Sun & McDonough (1989).

TABLE 5
Comparative analyses and CIPW Norms, tholeiites, Tamar Trough

Major and minor elements (wt %)			CIPW (anhydrous) Norms* (wt%)			Trace elements (ppm)			Rare Earth Elements (ppm)		
Oxide	TT	KT		TT	KT		TT	KT		TT	KT
SiO_2	55.21	49.52	Q	10.08	0.05	Ni	76	220	Rb	35	7
TiO_2	0.63	1.78	or	4.91	1.83	Cr	41	370	Sr	122	270
Al_2O_3	14.75	13.94	ab	13.56	21.32	Co	63	48	Y	23	23
Fe_2O_3	1.46	1.77	an	30.59	26.71	Sc	24	30	Zr	103	120
FeO	7.32	9.51	di	16.85	15.44	V	230	170	Nb	7	11
MnO	0.19	0.17	hy	20.42	27.63	Cu	82	53	Ba	215	80
MgO	6.69	8.54	mt	2.13	2.79	Zn	71	115	La	46	<20
CaO	10.82	9.41	il	1.20	3.45	Pb	9	11	Ce	29	<28
Na_2O	1.60	2.46	ap	0.21	0.72	Ga	16	20	Nd	-	<20
K_2O	0.83	0.30	Total	99.95	99.94	Th	3	<10			
P_2O_5	0.09	0.31	An/			U	3	<10			
Total	99.74	98.71	(Ab+An)%	69.3	54.1	∑Ni,Cr	117	590	∑La,Ce 75	<48	
Mg #	62.02	61.8	∑Q,or,ab								
Na_2OK_2O	1.93	8.2	(D.I.)	28.6	23.2						

Mg value and CIPW norms calculated at Fe_2O_3/ (FeO) 0.2. TT "Tamerton" basaltic plug (Frankford DQ 4920000 54302000). Analyst, XRF analyses, M. Loubser. KT Kelso DDH 2/27.5 m tholeiite flow (Beaconsfield DQ 4814000 54491000). Analyst, XRF analyses, Tasmanian Mineral Resources Laboratory.

TABLE 6
Most mafic, least evolved basalts, Tamar Trough

Basalt Type (criteria)	Ol.nephelinite (ab<5%, ne>5%)	Basanite (ab>5%, ab<an)	Alkali basalt-hawaiite (ne,hy<5%, ab<an)	Tholeiitic basalt (hy>10%,±Q)
CIPW norms (wt %)*				
Q	-	-	-	0.1-0.8
or	9.2	6.3–8.9	6.1–7.9	1.8–1.8
ab	3.0	7.5–12.6	18.4–24.9	21.2–21.3
an	13.1	18.7–21.5	22.8–23.6	25.49–26.7
ne	15.5	8.4–9.9	0.0–0.4	-
ol	25.3	19.5–21.9	17.8–22.9	-
di	21.9	21.3–23.2	15.4–18.3	15.0–15.4
hy	-	-	0.0–4.8	27.6–28.7
mt	3.7	2.9–3.3	2.7–3.5	2.8–3.0
il	5.5	4.7–4.9	3.8–4.0	3.4–3.6
ap	2.9	1.2–1.9	1.0–1.2	0,6–0.7
Fractionation indices				
$Mg/(Mg+Fe^{2+})$* %	62.1	62.3–66.2	64.8–67.9	58.9–61.8
An/(Ab+An)%	81.6	58.3–74.1	47.1–53.9	53.0–54.1
∑or, ab, ne (D.I.)	27.6	23.7–29.3	29.6–33.8	23.1–23.2
Key compatible elements				
Ni	305	210–220	175–200	200–250
Cr	341	220–290	278–420	350–370
V	173	140–200	120–240	155–170
Key incompatible elements				
Rb	20	24–30	16–28	7–22
Sr	975	770–980	522–1150	270–370
Ba	371	290–370	185–280	84–120
Y	34	21–29	18–26	22–240
Zr	323	230–285	110–200	120–165

Data from analyses in Sutherland (1969) and F.L. Sutherland unpublished trace element analyses and from Tables 3–5 this paper.
* Calculated at Fe_2O_3/ FeO ~ 0.2.

TABLE 7
Late fractionates, Tamar basalts

Pegmatoid type	In hawaiite	In basanite
CIPW norms (anhydrous wt %)		
or	9.3	6.7
ab	34.7	28.0
an	16.5	17.7
ne	-	1.7
ol	9.6	20.4
di	17.6	16.5
hy	0.4	-
mt	4.2	3.2
il	6.2	4.6
ap	1.5	1.0
Fractionation indices		
Mg/(Mg+Fe^{2+})%	51.7	59.9
An/(Ab+An)%	32.2	38.7
Σ or,ab,ne (D.I.)	44.0	29.8
Key compatible elements		
Ni	49	
Cr	42	
V	217	
Key incompatible elements		
Rb	33	
Sr	535	
Ba	159	
Y	33	
Zr	231	

Data from analyses in Sutherland (1969) and F.L. Sutherland unpublished trace element analyses.
CIPW norms and Mg values calculated at analysed Fe_2O_3/FeO ratios.

The expanded range of Tamar basalt geochemistry (Sutherland 1969 and this paper) mostly includes near primary to mildly evolved magmas (tables 4, 6, 8), but some of the more voluminous flows (Craigburn-East Arm, parts of Grindelwald plateau, Cocked Hat Hill – South Esk) represent more fractionated magmas, further depleted in compatible elements and enriched in incompatible elements (see table 4 for comparison). Limited post-eruptive differentiation occurs in some basalts, where pegmatoidal developments formed during prolonged cooling and volatile build-up; these later stage phases show increased depletions in compatible elements (Ni, Cr < 100 ppm) and greater enrichments in Zr, Rb, Y (table 7).

Key incompatible element ratios show distinct differences across the basalt types (tables 3 & 8). The alkaline basalts, relative to the subalkaline basalts, have lower Zr/Nb (3–6 *cf* 7–11) and higher Ba/La (8–35 *cf* 4–5), La/ Y (1–2 *cf* 1) and Ce/Y (2–5 *cf* 1–2) ratios. These differences relate to different degrees of partial mantle melting within the mantle sources that increasingly depleted various mineral phases. Irregular variations in some values, however, such as Ba contents and Ba/La and Ba/Nb ratios suggest some specific phase differences also exist within the sources. The Cocked Hat Hill hawaiite flow has the lowest Zr/Nb (3.3) and highest La/Nb (0.9) and Rb/Nb (0.9) ratios even when compared to its more evolved plug composition (Zr/Nb 3.9, La/Nb 0.6, Rb/Nb 0.5). Thus, some key element ratios changed perceptibly during fractionation even within a flow episode.

DISCUSSION

Correlations of the basalt dating and known palynological biozonation within the associated Tamar sequences are given in table 9. This forms a new, more rigorous framework for the sedimentological, erosive and eruptive history within the Tamar Trough since its inception.

Basalt Geochronology

The K-Ar and Ar-Ar dating identifies several separate volcanic episodes in the evolution of the Tamar Trough; these include three prominent volcanic intervals that extend from Middle Eocene (47–46 Ma) through Late Eocene (37–32 Ma) to Late Oligocene (25–24 Ma) time. Differences between K-Ar and Ar-Ar results on the same basalt can range up to 8 million years (Rowella and Cocked Hat Hill hawaiites), giving some limits for uncertainties in the dating. Discrepancies between the two dating techniques may be due to Ar loss from late-stage alteration (Cocked Hat Hill, 29 K-Ar *cf* 37 Ar-Ar Ma), and /or from contaminated degassing (Rowella, 40 Ar-Ar *cf* 47 K-Ar Ma). In such cases it was important to evaluate excess argon effects in the K-Ar dating material in the K-Ar ages, and this was done by inspection of Ar-Ar data. Even with dating discrepancies, likely basalt ages can be constrained through the associated palynological biozone ages, to indicate the more reliable date. Thus, the congruence of palynological age (Middle *N. asperus*) and Ar-Ar basalt age (37 Ma) at Cocked Hat Hill and also the matching palynological age (Upper *M. diversus* or *P. asperopolus* Zone) and K-Ar basalt age (47 Ma) at Rowella help confirm these radiometric dates.

The oldest Tamar basalt in the Middle Tamar channel through Rowella at 47 Ma ranks among the older Tasmanian eruptives, although this age is exceeded only by basalts on the eastern Tasman margin (Cape Portland, Bream Creek) and on King Island (59–70 Ma; Baillie 1987, Sutherland *et al.* 2002, Everard *et al.* 2004a, F.L. Sutherland and H. Zwingmann, unpublished data). The Rowella episode correlates with and extends the alkali basaltic activity known around Weldborough, NE Tasmania (46–47 Ma; Sutherland & Wellman 1986).

The most voluminous basaltic infillings were produced by the Late Eocene eruptives (37–33 Ma) in the Middle and South Tamar areas. Two major flows (Rosevears, Bredalbane) have Ar-Ar ages within experimental error (37 Ma), and with a further voluminous flow at East Arm and other flows in the Middle to South Tamar region (> 32–37 Ma), mark a peak in volcanism within the Tamar Trough. These massive outpourings caused considerable dislocations to Tamar courses including westward diversion of the South Esk from ancestral Tamar drainage. Basalts in the 33–38 Ma bracket also prevail elsewhere in Tasmania (Blessington, Thirlstane, Lillicos Beach, Melton Mowbray, Central plateau; Cromer 1980, Sutherland & Wellman 1986, Everard *et al.* 2004b). Indeed they may include extensive basalts through NW Tasmania, east of Waratah where interbedded sediments include the Upper *N. asperus* and Lower *P. tuberculatus* biozones (Brown & Forsyth 1984). Nevertheless, the Late

TABLE 8
Comparative key trace element ratios, Tamar and Tasmanian basalts

Basalt/key element ratios	Mg value	Zr/Nb	La/Nb	Ba/Nb	Rb/Nb	Ba/Th	Ba/La	La/Y	Ce/Y
Tamar 'mafic' basanite[1]	66	4.51	0.53	5.69	0.47	>29	10.7	1.29	3.29
Tamar 'mafic' alk basalt[2]	66	4.74	0.64	6.41	0.54	>25	10.0	1.39	3.06
Tamar 'mafic' hawaiite[3]	65	3.33	0.91	7.88	0.85	>26	8.67	1.50	3.65
Tamar 'mafic' ol basalt[4]	66	4.88	0.56	6.83	0.39	18.7	12.2	<5.0	3.15
Tamar primary hawaiite[5]	68	3.87	0.60	6.26	0.45	75.5	10.4	1.18	2.33
Tamar evolved hawaiite[6]	61	4.18	0.57	5.48	0.28	76.8	9.56	1.28	2.85
Longford alkali basalts av.[7]	65	4.63	0.13	6.93	0.50	-	11.6	1.20	3.10
NE Tas alkali basalt[8]	61	3.62	0.54	5.19	0.37	82.3	9.69	0.90	1.94
NE Tas evolved hawaiite[9]	59	4.86	0.79	5.86	0.52	76.8	7.46	1.94	3.96
NW Tas basanite[10]	62	3.39	0.62	6.74	0.68	86.3	10.9	1.81	3.28
Tasmanian seamounts[11]	67	3–5	0.5–1	5–8	0.3–1	64–99	9–13	0.9–1.9	2–3.8
Tamar Q tholeiite[12]	59	10.9	>0.4	8.07	0.73	–	>4.1	<1.11	<1.56
NE Tas Q tholeiite[13]	63	8.05	0.56	7.85	0.63	85.0	14.0	0.41	1.50
Loira Q tholeiite [14]	62	20.0	2.22	37.4	6.11	66.2	16.8	0.57	1.29
Tasmanian Q dolerite[15]	60	21.1	2.42	48.2	7.33	62.0	19.9	0.55	1.22

[1] Strathlyn (table 3). [2] Strathlyn (table 3). [3] Cocked Hat Hill (table 3). [4] Prospect Vale (table 3). [5] Rowella DDH2 (table 4). [6] Cocked Hat Hill quarry (table 4). [7] Longford alkaline basalts (this paper, Appendix B). [8]Weldborough Pass, Blue Tier (Sutherland *et al.* 2004). [9]George Rocks dyke (A. Spath analyst). [10] Currie, King Island, plug (Sutherland *et al.* 2004). [11] Balleny plume trace (Lanyon 1994). [12] Kelso DDH 1/ 51.6 (table 3). [13] North Pipers Brook (Sutherland *et al.* 2004). [14] "Tamerton", Supply Creek, Loira (A. Spath analyst). [15] Tasmanian chilled Jurassic dolerite average (Hergt *et al.* 1989).

TABLE 9
Summary of sedimentation/volcanism infill sequences, Tamar Trough

Age (Ma)	Epoch	Palynology biozone	Date	Basalt type	Area	Comments
0–22.5	Holocene- E. Miocene	'*T. pleistocenicus*- U. *P. tuberculatus*'		No definite records	Tamar Valley	Tamar, river erosion, sediments and soils
	E. Miocene?	U. *P. tuberculatus*?	?	ol.tholeiite?	S. Tamar	Sub-basalt deposits
23.5–32.5	E. Miocene- E. Oligocene	U. *P. tuberculatus*? M. *P. tuberculatus*- L. *P. tuberculatus*	? ? 24.7+	ol.basalt? hawaiite tholeiite	L-M Tamar	Shift of Tamar outlet, fluvial beds, erosion, lava infills, fluvial beds (dolerite gravels)
	E. Oligocene?					
32.5–37.0	L. Eocene	U. *N. asperus*- L. *N. asperus*	32.5* 33.7* 36.9a 37.0a	hawaiite basanite hawaiite hawaiite	M-S Tamar U. Tamar S. Tamar	Diversions of Tamar courses, erosion and fillings. Diversion of S. Esk from Tamar
37.0–47.0	M. Eocene	L. *N. asperus*- *P. asperopolus*	? ? 46.7+	basanite nephelinites hawaiite	M-S Tamar M. Tamar	Erosion, sediments, diversions of Tamar, lava infills
47.0–55.0	M. Eocene- E. Eocene	*P. asperopolus*- U. *M. diversus*			M-U Tamar	Trough erosion, fluvial deposits
55.0–65.0	Palaeocene	M-L *M. diversus*- *L. balmei*-			Tamar Trough	Infill sedimentation growth faulting
65.0–95	L. Cretaceous- M. Cretaceous	*F. longus*			TFZ TM	Main faulting, uplift Thermal upwelling

Epoch: L. Late, M. Middle, E. Early; Biozones U. Upper, M. Middle, L. Lower; from Glenn *et al.* (1999).
+ K-Ar date, * minimum K-Ar date, a Ar-Ar date.
Tamar areas: L. Lower, M. Middle, U. Upper, S. South. TFZ Tamar Fracture Zone; TM Tasman Margin.

Eocene Tamar basalts clearly form a major contribution to Tasmanian volcanism in this period.

The younger basaltic infillings in the Tamar Trough include the more confined Lower Tamar flows. Here, basal tholeiites are interbedded with Lower *P. tuberculatus* zone age beds and lie below hawaiite and transitional olivine basalt flows that overlie Lower-Middle *P. tuberculatus* age sedimentary beds dated between 24–25 Ma. Basalts with 20–25 Ma ages are particularly prevalent throughout the Tasmanian province (Sutherland & Wellman 1986, Sutherland *et al.* 2002, 2004, Everard *et al.* 2004b). Tholeiitic basalts are prominent and the Tamar Trough appears no exception, particularly if the olivine tholeiite in the South Tamar also fits here. So far, no later volcanism is known in the Tamar Trough to match the last phase of alkaline activity in northern Tasmania (9-20 Ma; McClenaghan *et al.* 1982, Baillie 1986, Sutherland *et al.* 1996, 2002, Everard *et al.* 2004b).

Palynology Zones

Many Tasmanian palaeobotanical sites have been studied, but only a few of the inland sites have radiometric basalt dates directly or indirectly associated with them (Wilmot Dam, Monpeelyata, Lemonthyme). Some of the most important sites lack such dates (Little Rapid River, Lea River), but are associated with basalts (Jordan & Hill 2002). The Tamar basalt dates provide new control points for palynology zones identified in accompanying sediments. Thus, the 37 Ma Ar-Ar age at Cocked Hat Hill provides constraints for the top of the Lower *N. asperus* zone which underlies this basalt, and only allows a limited erosive interval here before the Middle *N. asperus* zone (Glenn *et al.* 1999). Similarly, the 47 Ma K-Ar age at Rowella provides a peg within undifferentiated *P. asperopolus-M. diversus* Zone age sediments and suggests they belong to the *P. asperopolus* Zone on the Glenn *et al.* (1999) correlations. The 25 Ma date on the lower basalt at George Town would reposition the underlying L.-M. *P. tuberculatus* Zone correlation into the M. *P. tuberculatus* zone in the Glenn *et al.* (1999) correlation. The other basalt dates represent minimum ages, so are less precise for pegging biozonation ages. However, minimum dates of 32.5 Ma at Batman Highway, East Arm and 33.7 Ma at Loch Lea, Strathlyn are compatible with pre-basalt erosion into *N. asperus* age sediments.

The correlation of the palynology zones and absolute time scale is dependent on the time scale chosen for the correlations. Thus earlier correlations of basalts and palynology zones in Tasmania (Seymour 1989), differ from those given in this study, which are based on the Glenn *et al.* (1999) correlations. Uncertainties in previous Tasmanian palynological time correlations, which lacked direct dating, due to use of zones from outside Tasmania and to interpolations in the geomagnetic time scale, were discussed in Seymour (1989). Thus, a basalt age of 47 Ma (Rowella) in earlier correlations would lie at the base of Lower *N. asperus* zone and not within the *P. asperopolus* zone as given in this study. Similarly, basalt ages of 37 Ma (Grïndelwald, Cocked Hat Hill) would lie in the Upper *N. asperus* zone, not in the Middle *N. asperus* zone and the 25 Ma basalt age (George Town) suggests underlying beds are either Middle or Lower *P. tuberculatus*, zone age. The new Tamar study, thus, provides a firmer framework for Tasmania Early Eocene to Early Miocene palynological correlations.

Basalt petrogenesis

The Tamar basalts represent a range of alkaline to subalkaline magma compositions (fig. 3), but they lack the more undersaturated melilite-bearing types and the more evolved alkaline types found elsewhere in Tasmania (Sutherland *et al.* 2004, Zhang *et al.* 2006). The primary magma types identified in the Tasmanian basalt spectrum have been linked to different degrees of partial melting of mantle sources, initially estimated by portioning K_2O and P_2O_5 from the source into the melt (Frey *et al.* 1978, McClenaghan *et al.* 1982, Everard in Seymour 1989). The Tamar petrological range (olivine nephelinite to quartz tholeiite) would represent a range from 7 to 35% in degrees of partial mantle melting using that method. Uncertainties in precise elemental enrichments and melting processes within mantle sources, however, make such estimates very approximate. Thus, trace element inversion modelling on basalts with similar major element compositions to Tasmanian basalts can provide different sets of partial mantle melting degrees. Examples include 3–30% (Iblean basalts, Sicily; Beccaluva *et al.* 1998), 2–7% (Vogelsberg basalts, Germany; Jung & Marsberg 1998) and 4–11% (Nushan and Fangshan basalts, China; Zou *et al.* 2000). Comparison of these trace element contents with those of the Tamar basalts suggest the latter may have been produced by > 3–4% degrees of partial mantle melting (olivine nephelinite), > 4–6% (basanites), > 6–10% (alkali basalts-hawaiites), >9–15% (olivine tholeiite) and > 16–30% (quartz tholeiite). New studies show that many Tasmanian basalts include a deep seated metasomatic component to account for their enriched elements (Adam & Green 2006).

Trace element arrays

Trace element patterns, normalised to primitive mantle or chondrite values, show variations between the basalt types (figs 4, 5). Basanites and some alkali basalts and hawaiites show relatively subdued Rb, Ba, La, Ce and Sr in their profiles, but several have marked enrichments in Nb and relatively minor depletions in K, Ti and Y (fig. 4A–C). Among hy-normative alkali and transitional olivine basalts (fig. 4C), a Kelso olivine basalt is noticeably depleted in Ba, La, Ce and Sr; such depletions approach those shown by the Kelso quartz tholeiites (fig. 4D) and suggest a transitional tholeiitic affinity. The Kelso quartz tholeiites lack the positive Nb and negative K anomalies found in the more alkaline basalt patterns and show depletions in Rb and Sr; the patterns are quite distinct from the Tamerton quartz tholeiite pattern, which shows a classic Jurassic chilled dolerite pattern (Hergt *et al.* 1989), with strong depletions in Nb, Sr and Ti and significantly higher Rb, Ba, Th and K (figs 4C, 5).

More extended, primitive mantle-normalised, multi-element arrays are available for two prominent Tamar alkali basalts, the Rowella and Cocked Hat Hill basalts (fig. 5). Both show similar normalised REE arrays, that regularly decrease from LREE through MREE to HREE, and suggest magmas derived from a LREE-enriched source (fig. 5A). The extended primitive mantle-normalised patterns are marked by moderate depletions in Rb, K and Hf and enrichments in Cs, Nb, and Zr (fig. 5B, C). The fractionated Cocked Hat Hill hawaiite lacks any Eu anomaly, while noticeable depletions in Ni, Cr and Sc (table 4) suggest both olivine and clinopyroxene were the main fractionating phases in

evolving the hawaiites. The alkali basalt patterns contrast markedly to the Tamerton Jurassic pattern, which shows lower LREE and MREE, but higher HREE, and deficiencies in Nb, Sr, Ti; a minor Eu depletion suggests marked plagioclase crystallisation in its evolution (fig. 5), a feature not seen in Tasmanian Cenozoic basalts.

Trace element ratios

Most of the Tamar basalts show key trace element ratios that fall within the mantle array (Fitton *et al.* 1997) and within the range for HIMU (high μ) – related Oceanic Island Basalt (OIB) suites (table 8, fig. 6). The HIMU-like signatures (Weaver 1991) occur among Tasmanian basalts and also in the Tasmanian seamounts off eastern Tasmania (Lanyon *et al.* 1993, Lanyon 1994, Crawford *et al.*, 1997). These basalts represent a mantle source enriched in Ta and Nb, relative to LREE, giving low Zr/Nb ratios (av. 3.85 ± 1.1) compared to other OIB sources. Part of this low Zr/Nb signature, however, may relate to the degree of partial melting in the mantle sources, as Zr/Nb increases with degree of saturation of the basaltic magmas (see table 8). Thus, it is important to compare similar ranges of basalt types. This may explain Tamar olivine nephelinite ratios that lie outside the Tasmanian seamount range where the lithology is largely based on basanites and alkali basalts. HIMU types also show relatively high values of μ (high $^{238}U/^{204}Pb$ ratios) that produce high time-integrated $^{206}Pb/^{208}Pb$ signatures (>19), along with low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ values. No isotopic data are available for Tamar basalts, but the trace element ratios closely match basalts that carry such signatures at Weldborough and Table Cape (table 8). The origin of this HIMU imprint in southern Australasia and Antarctic basalts is uncertain, but may relate to mantle events around 80–100 Ma; it possibly stems from a large plume head or a series of small plumes developed with late Gondwanan break-up (see Lanyon *et al.* 1993, Lanyon 1994, Sutherland 1994, Crawford *et al.* 1997). The HIMU character in some basalts within Tasmania and in the Tasmanian seamounts (μ 19–20.3; Ewart *et al.* 1988, Lanyon *et al.* 1993, Lanyon 1994, Crawford *et al.* 1997, Sutherland 2003, Zhang *et al.* 2006) becomes more pronounced in many Antarctic basalts (μ > 20.5; Rochell *et al.* 1995, Panter *et al.* 2000). This has prompted suggestions that the HIMU-imprint may reflect variable subduction-related metasomatism of the underlying subcontinental lithospheric mantle (SCLM) during the Late Mesozoic (Finn *et al.* 2005).

HIMU signatures do not normally extend to tholeiitic lavas, and the Tamar tholeiites have distinctly different trace element ratios to the Tamar alkaline suites (fig. 8). The Kelso quartz tholeiites have Zr/Nb ratios (10.9) that lie at the high end for Tasmanian Cenozoic tholeiites (Zhang *et al.* 2006), but with their Ti/V ratios (63-67) remain quite distinct from the Tamarton tholeiite (Zr/Nb 14.7, Ti/V 16) and typical Tasmanian Jurassic dolerites (Hergt *et al.* 1989).

Mantle Sources

The Tamar alkaline parental magmas mark several melting episodes derived from a garnet peridotite source based on its range of normalised trace element ratios (La/Nb_N 0.55-0.67; Ce/Y_N 5.52-12.0). This Tasmanian mantle source includes a HIMU imprint introduced before 47 Ma (Rowella hawaiite).

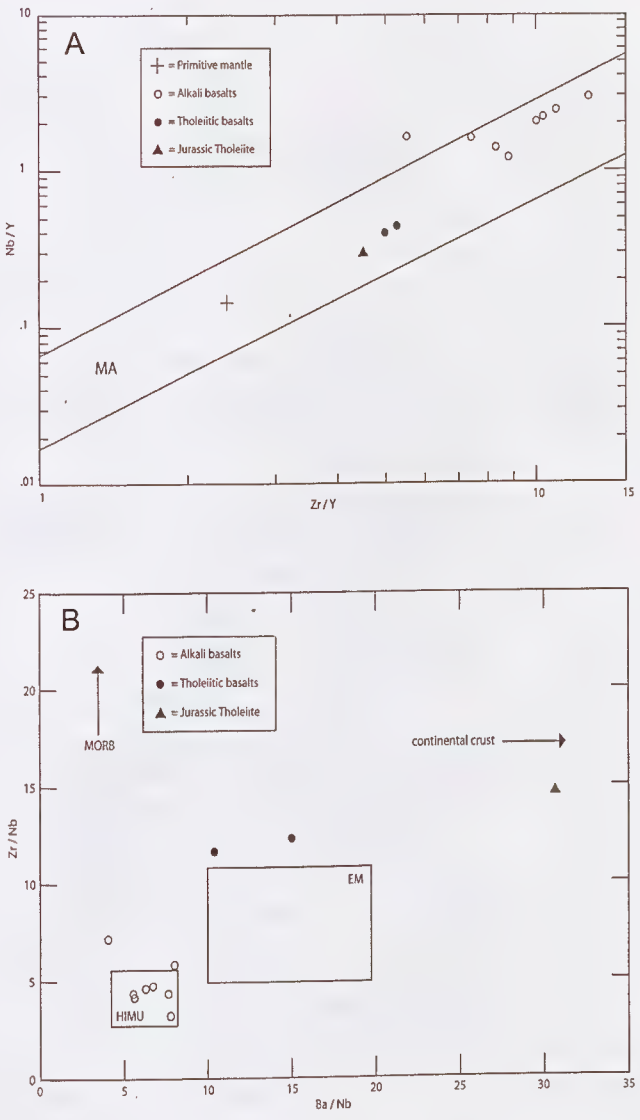

FIG. 6 — Incompatible element ratio plots for Tamar basalts. (A) Nb/Y against Zr/Y (MA Mantle Array; field after Fitton et al. 1997). (B) Zr/Nb against Ba/Nb (MORB Mid-Ocean Ridge Basalt, EM Enriched Mantle, HIMU High-mu mantle; fields after Weaver 1991).

More details of the peridotite source, its variations, and depths of magma generation for the HIMU-related Tamar basalts come from the more extended trace element data for the Rowella and Cocked Hat Hill basalts. The somewhat low La/Yb_N of these basalts (9.5–10.4), within the primary alkaline range in Tasmania (8–42; Sutherland *et al.* 2004, Zhang *et al.* 2006), suggests between 10 to 20% degrees of partial mantle melting generated these voluminous Tamar magmas. Plots of Ce/Yb_N (7.7, 9.6) against Yb_N (9.24; 8.71) for the two rocks suggest large clinopyroxene (cpx) to garnet (gnt) ratios were left in the residual source, between 14.0–14.5 cpx and 1–0.5 gnt based on such modelling by Jung & Marsberg (1998).

Depths of magma segregations can be estimated using Ce/Yb and Sm/Yb plots (Ellam 1992). In the Tamar hawaiites, Ce/Yb (27.7, 34.5) and Sm/Yb (3.0, 3.86) suggest magmas that rose from 70–90 km depth. The mantle regimes involved in basaltic melting can be discerned using Nb/La to La/Yb ratio plots (Abdel-Rahman 2002). The Tamar hawaiite

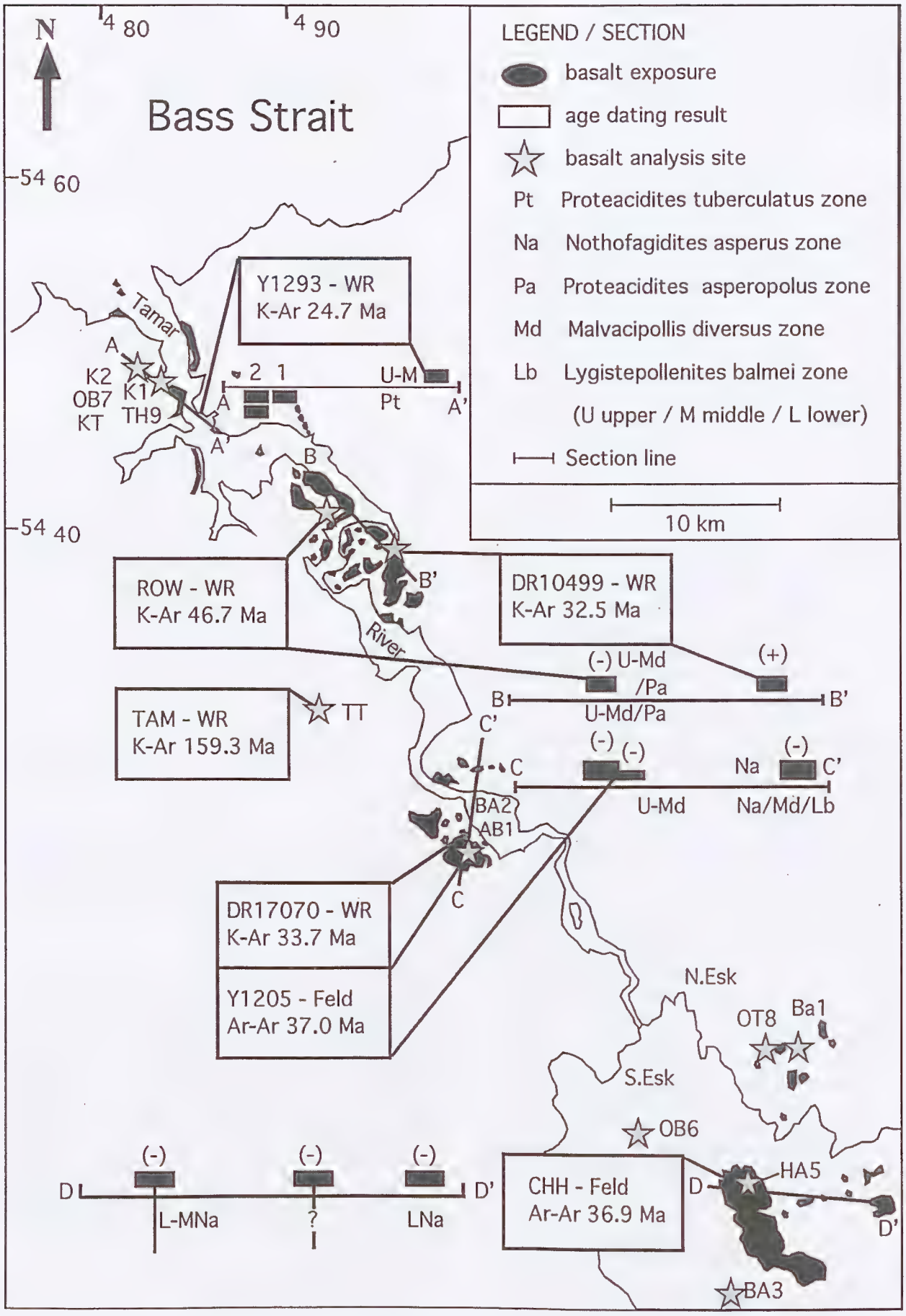

FIG. 7 — Dated and analysed basalt sites, Tamar areas, showing relationships to known palynology zones within sequences. Horizontal sections (A-A', B-B', C-C' D-D') are schematic cross-sections from the map. Analysed basalts are coded from the analytical tables and reversed (-) and normally (+) magnetised basalts are designated where known.

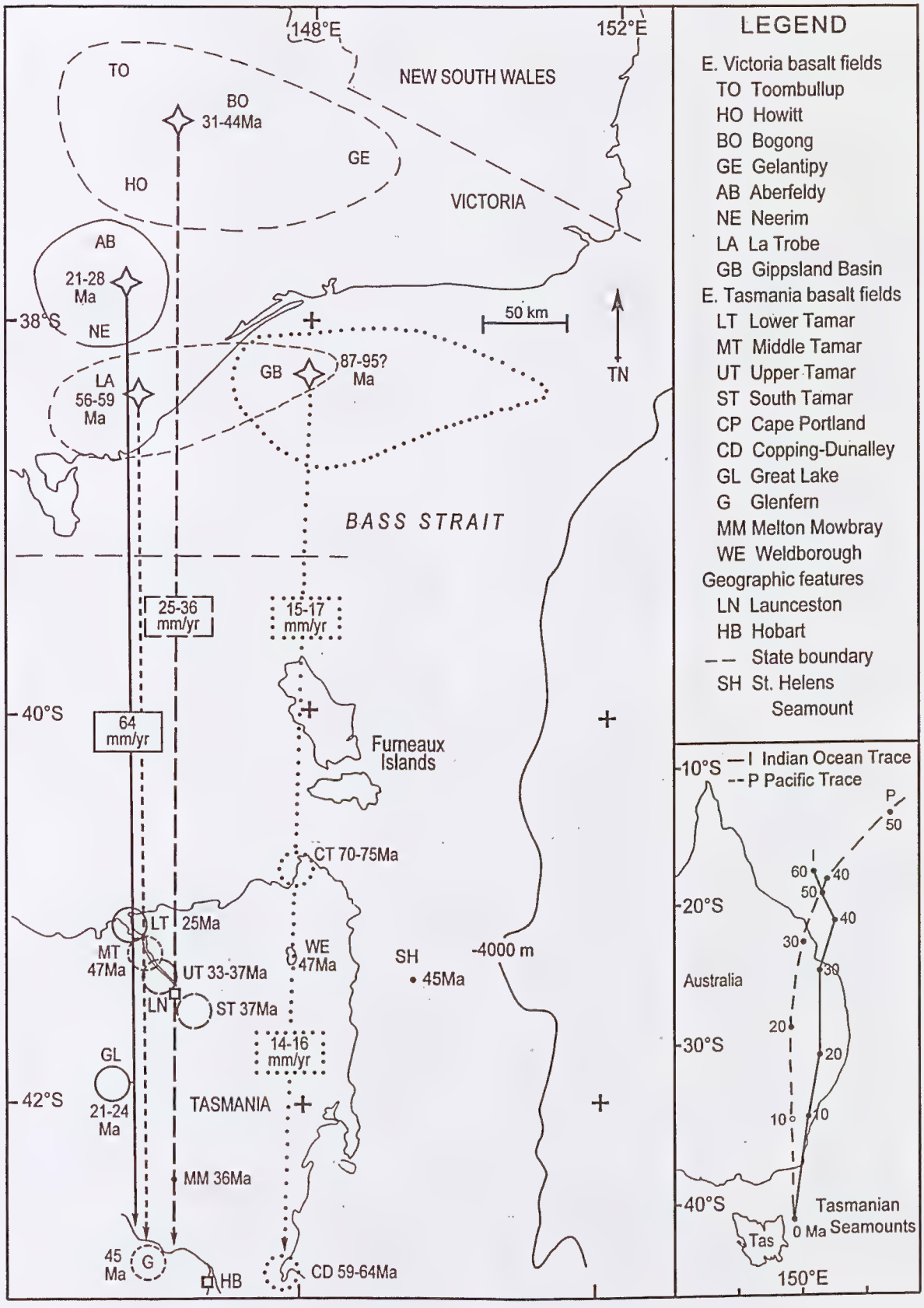

FIG. 8 — Tamar, east Tasmania and east Victoria basalt ages, related to migratory paths from Tasman margin plume sources (stars); ages come from Birch (2003), Sutherland et al. *(2004), Everard* et al. *(2004a) and herein. Victorian magma sources and paths include Gippsland Basin (dotted lines), La Trobe (short dashed lines), North-east (long dashed lines), Centre- east (solid lines), with migration rates (boxes). Other Tasmanian basalt dates are left out for clarity. The depicted migration rates for each migration line are based on the Victorian-Tasmania basalt ages, for comparison with Australian plate motion paths for those times. The top inset lists basalt fields. The bottom inset shows Australian plate motion paths from 60 Ma to a present Tasman Sea plume position, from Indian Ocean (I) and Pacific (P) hotspots.*

ratios (Nb/La 1.65, 1.75; La/Yb 14.0, 15.5) suggest their magmas originated well within the asthenospheric field. Additional mantle affinities can be delineated by plotting Ce/Nb against Th/Nb ratios (Song *et al.* 2001). The Tamar hawaiite values (Ce/Nb 1.20, 1.28; Th/Nb 0.08, 0.07) place them with plume-related basalt magmas, close to the OIB field and Primitive Mantle ratios.

The Tamar olivine nephelinites are moderately depleted in Rb (20 ppm) and Ba (371 ppm) compared with some Tasmanian nephelinites (Rb 29–40, Ba 530–724 ppm). In this respect, they approach the Scottsdale nephelinite which is low in these elements relative to the standard HIMU component, possibly reflecting residual phlogopite in the source (see Sutherland *et al.* 2004). Whatever the precise origins of the HIMU- and garnet-bearing sources for the Tamar alkaline basalts, the Tamar tholeiites also reflect variations in source inputs. Tasmanian olivine tholeiites include co-existing types that differ in trace element and Pb isotope signatures, even at similar Mg-values and compatible element contents (Sutherland 2003, Sutherland *et al.* 2004). One group includes mantle-derived and near- HIMU Pb isotopic types and has higher Rb, Ba and Y values similar to those shown by Tamar olivine tholeiites. Comparisons of the Tamar alkaline basalts with the adjacent Longford alkaline basalts (appendix B, fig. 4, table 8) show little differences in their basic geochemistry, although the Longford rocks tend to have relatively low Na_2O/K_2O (2.0–2.3) and higher Sr (> 1000 ppm) values than their Tamar equivalents.

Interpretive Model for Tamar Trough Evolution

The new framework established for the Tamar Trough sequences, through combined palynological and basalt dating (fig. 7), allows further interpretations of its tectonic-thermal evolution. Initiated after Mid-Cretaceous to Early Palaeocene thermal uplift and rifting along the Bassian Tasman margin (Gleadow 1996, O'Sullivan *et al.* 2000, Cummins 2001), the Trough became a locus for sedimentation associated with the ancestral Tamar drainage. Volcanism did not begin until about 47 Ma during the *P. asperopolus* Zone sedimentation, some 15-20 million years after rifting. Thus, the reasons behind the timing of volcanism need explaining beyond the Tamar faulting itself and consideration within the general Tasmanian-Bassian Cenozoic volcanism story.

During the early Tamar sedimentation, Tasmanian volcanism was largely restricted to the far eastern margin, between 70–76 Ma in north-eastern Tasmania (Everard *et al.* 2004a, F.L. Sutherland and H. Zwingmann unpublished data) and between 59–65 Ma in south eastern Tasmania (Baillie 1987, Sutherland *et al.* 2004, Everard *et al.* 2004b). These dates imply potential southerly migratory volcanism, which back-tracks on slow Southern Ocean spreading rates to 85–95 Ma Gippsland Basin rifting and attendant Victorian margin volcanism (fig. 8). The Gippsland rift was a failed spreading arm of the Tasman Sea spreading triple point, a structure linked to plume volcanism (Sutherland 1994). The precise nature of this plume path and its geochemical relationships to the Tasmanian seamounts and Tasmanian basalts, however, have various interpretations (Lanyon *et al.* 1993, Crawford *et al.* 1997, Gaina *et al.* 2000, Sutherland *et al.* 2004). Nevertheless, the timing of HIMU-related alkali basalts (45–47 Ma) extending east from the Tamar Trough to Weldborough and St Helens Seamount and south to Glenfern in the Derwent Valley (Sutherland *et al.* 2004, Everard *et al.* 2004b) is consistent with suggested Gippsland –Tasmanian Seamounts plume positions.

Recent studies of hotspot plumes, such as the Gippsland plume, suggest they may mark both metasomatic and magmatic processes related to triple junctions, failed rifts and ancient sutures, rather than necessitating deep-mantle plumes (Smith 1993, Finn *et al.* 2005, Sears *et al.* 2005). This is compatible with a proposed model for quasi-continuous, but episodic Tasmania volcanism that resulted from lithospheric drift of eastern Australia over an extended Tasman Sea plume zone (Sutherland *et al.* 1989). Furthermore, precise Tasmanian basalt ages (Sutherland *et al.* 2004, Everard *et al.* 2004b) and better-controlled Australian plate motion paths back to 80 Ma (Sutherland 2003) now allow more detailed testing of the Tasman margin magma source model for Tasmanian volcanism. A fuller development will be given elsewhere, but for this Tamar Trough study a simplified model that relates the Tamar basalts to migratory links through eastern Victoria is presented in figure 8.

The proposed model predicts that the prominent Tamar alkaline volcanism dated at 46–47, 34–37 and 24–25 Ma and also the Early Oligocene tholeiites are a consequence of drift of the area over magma sources that previously fed the older eastern Victorian basalt fields. It also predicts the lack of Late Neogene (<24 Ma) volcanism in the Tamar sequence, as no basalt sources of appropriate age occur in eastern Victoria to intersect the Tamar track.

The periodic events where massive basalt flows entered the Tamar drainage between 47–24 (?) Ma, disrupted extant river courses and sedimentation regimes and also introduced resistant basalt bulwarks within the erosional cycles. In the last 20 Ma, the Tamar evolution has largely progressed through erosive/ sedimentary cycles linked to Tasmanian climatic and sea level changes, unimpeded by volcanic disruptions.

ACKNOWLEDGEMENTS

This study is dedicated to Walter Sutherland, former librarian, Launceston Regional Library, who greatly encouraged the earlier studies on the Tamar volcanic sequences by the first author. The present study initiated at the Australian Museum was approved by the then Director, Dr Michael Archer, with funding support from the Australian Museum Trust. Assistance with technical and script preparation came from Ross Pogson, Sue Folwell and Roger Springthorpe, Australian Museum. Samples for some of the analyses were provided by Noel Kemp, Geologist, Tasmanian Museum, Hobart. Basalt samples were prepared and analysed with the assistance of Les Hay, Chief Chemist, Jafar Taheri, Richie Woolley, Shane Heawood and David Shaw, Tasmanian Mineral Resources, with additional analyses by Maggie Loubser, Geology Department, University of Pretoria, and Andreas Spath, Geology Department, University of Cape Town, South Africa. Additional support for the project came from Peter Baillie, TGS-NOPEC Geophysical Company, West Perth, Western Australia. The script was read by Dr Larry Barron, Research Associate, Australian Museum. Constructive reviews were made by Drs Greg Jordan, School of Plant Science, University of Tasmania, Hobart, and Ian Roach, Department of Earth and Marine Sciences, Australian University, Canberra, ACT. S.M. Forsyth and J.L. Everard publish with permission of the Director of Mines, Mineral Resources Tasmania.

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(accepted 2 October 2006

APPENDIX A
Petrographic description of analysed, dated and new Tamar Trough basalts

Quartz tholeiite: West of Tamerton, Loira (DQ 920302) (DR 17074).
See plate 2F

Quartz tholeiite: Kelso DDH 1/51.55m (DQ 819489).
Olivine phenocrysts (5–10% ≤ 1 mm but mostly ~ 500 µm) grade into an intergranular to intersertal groundmass, with patches of "black glass". Most glass areas are completely altered to pale brown, coarsely fibrous material, although some remain largely fresh.

Groundmass plagioclase laths range from microphenocrysts (≤ 700 x 150 µm) to acicular laths (~ 100 µm long, 200–300 µm long) and are accompanied by interstitial granules of colourless augite (50–100 µm), subordinate olivine, and a black glassy mesostasis, partly resolvable into a dense dissemination of blebs and microlites of an opaque mineral.

Quartz tholeiite: Kelso DDH1 (DQ 819489) (G400356).
Fresh, equant olivine crystals (up to 1 mm), and less abundant plagioclase in narrow laths (typically 300–500 x 50–100 µm, but grading down to microlites) are set in an abundant mostly clear glass (70–80%). The pale to yellow-green unaltered glass in places passes into a turbid, dark orange-brown to nearly opaque material. Between fresh and unaltered glass, plagioclase laths are surrounded by brown altered glass and probably acted as nuclei during the alteration of glass. A few irregular vesicles and amygdales contain very fine-grained, brownish material.

Quartz tholeiite: Kelso 2/27.5 m (DQ 814491).
Numerous polygonal euhedra and subhedra of olivine (mostly 500 µm–1 mm across) and plagioclase laths (≤ 1 mm x 150 µm) grade down into a groundmass in which inhomogeneous black glass contains elongate to radiating trichites of plagioclase and uneven disseminations of opaque dust. Numerous irregular vesicles (≤10 mm) are lined with fibrous zeolite (phillipsite?) or pale yellow-brown, isotropic to kelyphytic material (palagonite?); some contain carbonate.

Transitional olivine basalt: Kelso DDH 2/7.0 m (DQ 814491).
Numerous, mostly corroded and partly altered, olivine phenocrysts (≤ 1mm) lie in a medium- to fine-grained holocrystalline intergranular groundmass with a marked flow lamination.

The groundmass contains aligned plagioclase laths (200–400 µm long), interstitial granules of colourless augite (10–50 µm), abundant well-crystallized opaque minerals in equant grains (10–40 µm) and acicular laths (≤ 100 x 5 µm) and a mesostasis enclosing tiny needles of apatite. Sparse, nearly round amyglades (≤ 1mm) contain granular carbonate.

Olivine basalt: Prospect Vale, New Bass Highway (EQ 106068) (L 10).
See plate 2A

Hawaiite: Cocked Hat Hill (EQ 16810365) (R010199).
Relatively abundant olivine phenocrysts (≤ 3.5 mm, but mostly 500 μm–1 mm) and rare glomerocrysts grade down into a fairly coarse-grained intergranular groundmass consisting of plagioclase in laths and irregular anhedra (mostly 500 μm–1 mm long), titaniferous augite granules (100–200 μm across), elongate (100–400 x 10–20 μm) opaque grains and tiny biotite flakes (≤ 50 μm) and acicular apatite. A few rounded amygdales (≤300 μm) are filled with nepheline. Some alteration appears on margins and fractures of olivine phenocrysts along with similar patchy material in the groundmass.

Hawaiite: South Esk River, near Sawpit Ford (EP 16439505) (R0011953, PTH 3).
Subhedral olivine phenocrysts (mostly 400 μm–1 mm, rarely ≤ 1.5 mm across) and glomerocrysts are partly altered to "iddingsite." The coarse-grained intergranular groundmass consists of plagioclase laths (500 μm–1 mm) and tabular zoned sections, titaniferous augite granules (≤150 μm) and elongate (150–400 x 10–20 μm) to equant angular opaque grains. Sparse patches of indeterminate mesostasis contain yellow-brown alteration products and opaque dust.

Hawaiite: South Esk River, near "Leighlands" (EP 17006451) (R011954, PTH4).
Olivine phenocrysts (500 μm–1 mm) lie in an intergranular to intersertal groundmass of plagioclase laths (1 mm), titaniferous augite granules and a turbid mesostasis which includes acicular opaque grains (≤200 μm long), titaniferous augite, low birefringence phases and brownish alterations and approaches "black glass."

Hawaiite: South Esk River, near "Rosebank" (EP 17109341) (R011955, PTH 5).
Partly altered olivine crystals and phenocrysts (500 μm–1 mm) lie in an intergranular groundmass of plagioclase laths (500 μm–1 mm), titaniferous augite granules and elongate opaque grains. Small (500 μm – 1 mm) segregations and amygdales are filled with feldspathoidal or zeolitic material.

Hawaiite: Rowella DDH 2, 117.08 m (DQ 930413) (CHH).
See plate 2E

Alkali basalt: Rosevears Estate Vineyard, Strathlyn (EQ 007233) (DR 17385).
See plate 2B

Basanite: Rosevears Estate Vineyard, Strathlyn (EQ 006233) (DR 17384).
See plate 2C

Basanite: Midland Highway bridge, Perth (EP 152962) (R010199, CHH).
Microphenocrysts of olivine (20%) up to 800 μm across, but mostly ≤ 500 μm, accompany subordinate microphenocrysts of titaniferous augite (up to 2mm across, but commonly ≤ 1 mm), which in places form glomerocrysts or rosettes.

The intergranular groundmass contains granules of titaniferous augite (typically 50–200 μm across), some sparse plagioclase laths (typically 150–600 x 15–50 μm) and equant angular opaque grains (typically 40–120 μm across). A low birefringence mesostasis contains zoned alkali feldspar and clear nepheline. A few small segregations contain mosaics of nepheline and very finely acicular apatite. An amygdale 1.5 mm across contains radiating sheaves of a zeolite (?) mineral, possibly phillipsite.

APPENDIX B
Whole rock XRF element analyses, Longford Basin basalts

Major oxides				Trace elements			
wt %	L1	L2	L3	ppm	L1	L2	L3
SiO_2	46.14	45.82	47.07	Ni	240	210	240
TiO_2	2.18	2.18	1.98	Cr	270	280	290
Al_2O_3	14.20	13.99	14.20	Co	58	55	55
Fe_2O_3	3.01	2.30	3.10	Sc	20	21	20
FeO	8.60	9.37	8.15	V	130	125	120
MnO	0.17	0.17	0.17	Ba	370	310	280
MgO	9.65	10.22	9.74	Rb	23	23	22
CaO	9.37	9.36	8.79	Sr	1300	780	1000
Na_2O	2.54	2.65	2.75	Y	23	21	24
K_2O	1.29	1.20	1.19	Zr	230	210	200
P_2O_5	0.55	0.56	0.45	Nb	47	51	41
H_2O+	1.85	1.76	1.92	La	29	27	27
CO_2	0.06	0.05	0.15	Ce	75	74	59
SO_3	0.00	0.01	0.01	Nd	30	38	34
				Pb	<10	<10	<10
Total	99.61	99.64	99.67	Th	<10	<10	<10
				U	<10	<10	<10
Na_2O/K_2O	1.97	2.21	2.31	Cu	59	59	54
Mg value*	64.21	65.27	65.20	Zn	120	115	120
An%*	51.00	51.59	48.16	Ga	21	22	21
D.I.*	29.72	29.09	31.04	Σ Inc.	588	566	605

* Calculated at Fe_2O_3/ FeO= 0.2. D.I. = Σ or, ab, ne. Σ Inc. = Σ Ni, Cr, Co, Sc.
L1. Alkali olivine basalt. "Karalta", Pateena Road, Longford (EP 09878818).
L2. Alkali olivine basalt. "Glendessary" via Evandale, Longford (EP 18849729).
L3. Transitional olivine basalt. Rail cutting, E of Longford, Longford (EP10929628).

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